THE UNIVERSITY OF HULL

The Synthesis and Properties of Liquid Crystals for Twisted Nematic and Ferroelectric Displays

being a Thesis submitted for the Degree of Doctor of Philosophy

in the University of Hull

by

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Summary of Thesis submitted for PhD degree

by Michael Hird, BSc, CChem, MRSC

on

The Synthesis and Properties of Liquid Crystals for Twisted Nematic and Ferroelectric Displays

This thesis is concerned with the synthesis, characterisation and physical properties of liquid crystal materials which (i) improve the switching speeds and multiplexability of twisted and supertwisted nematic display devices, (ii) exhibit the smectic C phase and are suitable for use as host materials for ferroelectric display devices, (iii) exhibit the nematic phase and have high polarisabilities and high optical anisotropies (birefringence).

(i) 4-Alkoxy- or 4-alkyl- 4'-cyanobiphenyls and 4-cyanophenyl 4-alkoxy- or 4-alkyl-benzoates have a positive dielectric anisotropy which is required to be large in order to provide fast switching speeds in twisted nematic display devices. The use of lateral fluoro-substituents can provide high dielectric anisotropies by breaking up antiparallel associations of the parent systems and by adding to the dipole. A range of fluoro-substituted cyanophenyl benzoate esters was prepared to provide dopants of high positive dielectric anisotropy and to provide information as to which fluoro-substitution patterns provide the most favourable results.

(ii) Ideal host materials for the ferroelectric display device are very difficult to obtain because of the need for low melting points, large smectic C ranges, low viscosities and large negative dielectric anisotropies. Excellent ferroelectric host materials have been prepared by utilising two *ortho* difluoro-substituents in terminal alkoxy- and alkyl- substituted 1,1':4',1"-terphenyls. This arrangement of lateral fluoro-substituents provides a narrow molecule which minimises viscosity and upholds smectic C phase thermal stability whilst providing a lateral dipole which leads to negative dielectric anisotropy.

(iii) A 2,6-disubstituted naphthalene moiety has been used in conjugation with an ethynyl linking group to give nematic materials of very high optical anisotropy.

The synthesis of the compounds included in this thesis required the development of extremely useful and interesting palladium-catalysed cross-coupling procedures including some novel selective couplings. This convergent approach to synthesis is very advantageous and provides high product yields.

ACKNOWLEDGEMENTS

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The Synthesis and Properties of Liquid Crystals for Twisted Nematic and Ferroelectric Displays

Liquid crystal display devices have only recently become widely available and represent a tremendous technological advance in providing both small, high contrast display devices of low power consumption for use in portable equipment and larger, back-lit, public information display devices. More recently miniature colour television displays utilising liquid crystals have become available based on twisted nematic technology. The ferroelectric display device is potentially important due to the promise of very fast switching speeds and high level multiplexability in large and small displays.

This thesis is concerned with the synthesis, characterisation and physical properties of liquid crystal materials which (i) improve the switching speeds and multiplexability of twisted and supertwisted nematic display devices, (ii) exhibit the smectic C phase and are suitable for use as host materials for ferroelectric display devices, (iii) exhibit the nematic phase and have high polarisabilities and high optical anisotropies (birefringence).

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a narrow molecule which minimises viscosity and upholds smectic C phase thermal stability whilst providing a lateral dipole which leads to negative dielectric anisotropy.

(iii) The use of a 2,6-disubstituted naphthalene moiety in conjugation with an ethynyl linking group and other moieties conducive to high polarisability provides nematic materials of very high optical anisotropy.

The synthesis of the compounds included in this thesis required the development of extremely useful and interesting palladium-catalysed cross-coupling procedures including some novel selective couplings. This convergent approach to synthesis is very advantageous and provides high product yields.

Publications

(i) Papers

(a) The Synthesis and Transition Temperatures of some Lateral Fluoro-substituted 4-cyanophenyl and 4-cyanobiphenyl-4'-yl 4-alkoxy- and 4-alkyl- benzoates (*Mol. Cryst. Liq. Cryst.*, 1989, **172**, 165).

(b) The Synthesis and Transition Temperatures of some 4,4''-Dialkyl- and 4,4''-Alkoxyalkyl- 1,1':4',1''-terphenyls with 2,3- or 2',3'- Difluoro-substituents and some of their Biphenyl Analogues (*J. Chem. Soc., Perkin Trans. 2,* 1989, 2041).

(ii) Patent Applications

(a) Lateral Cyanoterphenyls (B.P. 8724458), (b) Laterally Fluorinated 4-cyanophenyl and 4-cyanobiphenyl-4'-yl benzoates (B.P. 8804330), (c) Difluorinated Terphenyls and their use in Liquid Crystal Materials (B.P. 8806220), (d) Fluorinated Oligophenyls and their use in Liquid Crystal Materials (WO 89/02425),
(e) 2,3-Difluorobiphenyls (WO 89/08687), (f) Derivate des *p*-Terphenyls bzw. *p*-Quaterphenyls (DE 3807956 A1), (g) 2,3-Difluorbiphenyle (DE 3807861 A1).

(iii) Conferences

Papers were presented at the following conferences.

(a) The Third British Liquid Crystal Society Annual Conference, Glasgow, March 1988, (b) The Twelfth International Liquid Crystal Conference, Freiburg, August 1988, (c) The Fourth British Liquid Crystal Society Annual Conference, Sheffield, April 1989, (d) The Royal Society of Chemistry Autumn Meeting, Loughborough, September 1989.

CONTENTS

2.4 **Synthetic Schemes** (1-37, see below)

2.5 **Synthetic Methods**

INTRODUCTION

1.1 Historical Background

The discovery of liquid crystalline states of matter occurred in 1888 when the Austrian botanist Reinitzer[1] observed that cholesteryl benzoate melted at 145.5 °C to a turbid, milky fluid. The melt only became clear and transparent at 178.0 °C (a transition which was found to be exactly reversible on cooling). Physicist Lehmann[2-4] was also working on a similar investigation at this time and in 1889 he described the unusual appearance as consisting of 'living crystals' and established that it involved a new state of matter which he called the *liquid crystal* phase.

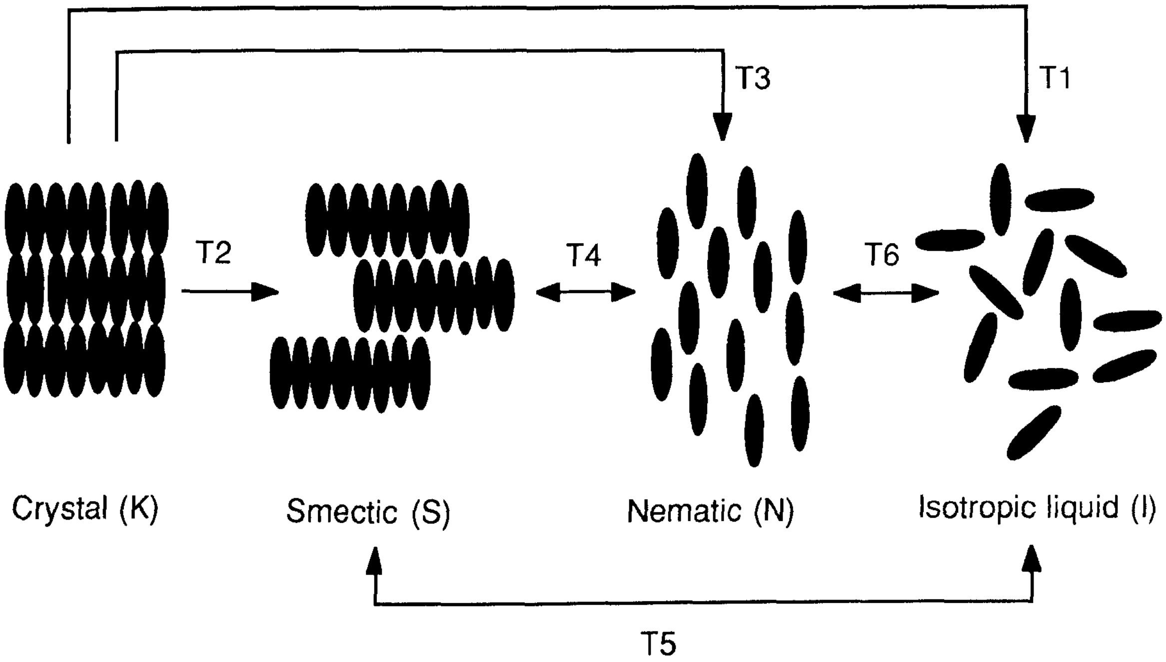
The existence of this new phase surprised the scientific community and was met with some disbelief, being passed off as colloidal effects due to the suspension of small crystals in the isotropic liquid or as impurities causing an emulsion.

In 1922, as the result of detailed microscopic studies, Friedel[5] was able to characterise three distinct types of liquid crystal phase. He named them *'nematic'* (after the Greek term *nematos* meaning thread-like), *'cholesteric'* (because, at the time, most compounds exhibiting this phase were derivatives of cholesterol) and *'smectic'* (after the Greek term *smectos* meaning soap-like). Although Friedel did not identify the existence of more than one smectic phase, this general classification still remains today.

In 1964 Fergason[6,7] reported on the use of cholesteric liquid crystals as temperature indicators, an area which still attracts much research attention today. However, the main driving force behind liquid crystal research was the realisation in the 1960s that liquid crystals could be used in flat-panel electrooptic display devices; the first such device was demonstrated by the Radio Corporation of America but only functioned at 80 °C. In 1968 Heilmeier[8,9] demonstrated a liquid crystal display device operating at room temperature and in 1971, Schadt and Helfrich[10] invented the twisted nematic display device. The discovery of the cyanobiphenyls by Gray *et al.*[11,12] in 1973 provided stable, room-temperature nematic materials which enabled the manufacture of marketable twisted nematic display devices (see also Applications of Liquid Crystals, p 23). Today, most research and development in the liquid crystal field is connected with display devices, but there is increasing research interest in liquid crystal polymers.

1.2 General Aspects of Liquid Crystals

A material is defined as a crystalline solid when the structure has long-range order of the molecular positions in three dimensions. A fully ordered crystal will also have long-range orientational ordering of its constituent molecules.[13]



Possible Phase Transition Sequences for Mesogenic Compounds

Figure 1

When a fully ordered molecular crystal is heated the thermal motions of the molecules within the lattice increase and eventually the vibrations become so intense that the regular arrangement of molecules is broken down with the loss of long-range orientational and positional order to give the disorganised isotropic liquid (T1, Figure 1). The temperature at which this process occurs is called the melting point and the heat absorbed by the molecules is the latent heat of fusion. However, this process, which takes a compound from being very well ordered to being totally disordered in one step is a very destructive one, which is not universal for all compounds. For many compounds, this process occurs by way of one or more intermediate phases as the temperature is increased. These phases are called *mesophases* and some of these mesophases are liquid crystalline. Liquid crystal phases have properties which are intermediate between those of the fully ordered crystalline solid and the isotropic liquid; liquid crystal mesophases are fluids which, due to partial orientational ordering of the constituent molecules, have material properties such as permittivity, refractive index, elasticity and viscosity which are anisotropic.

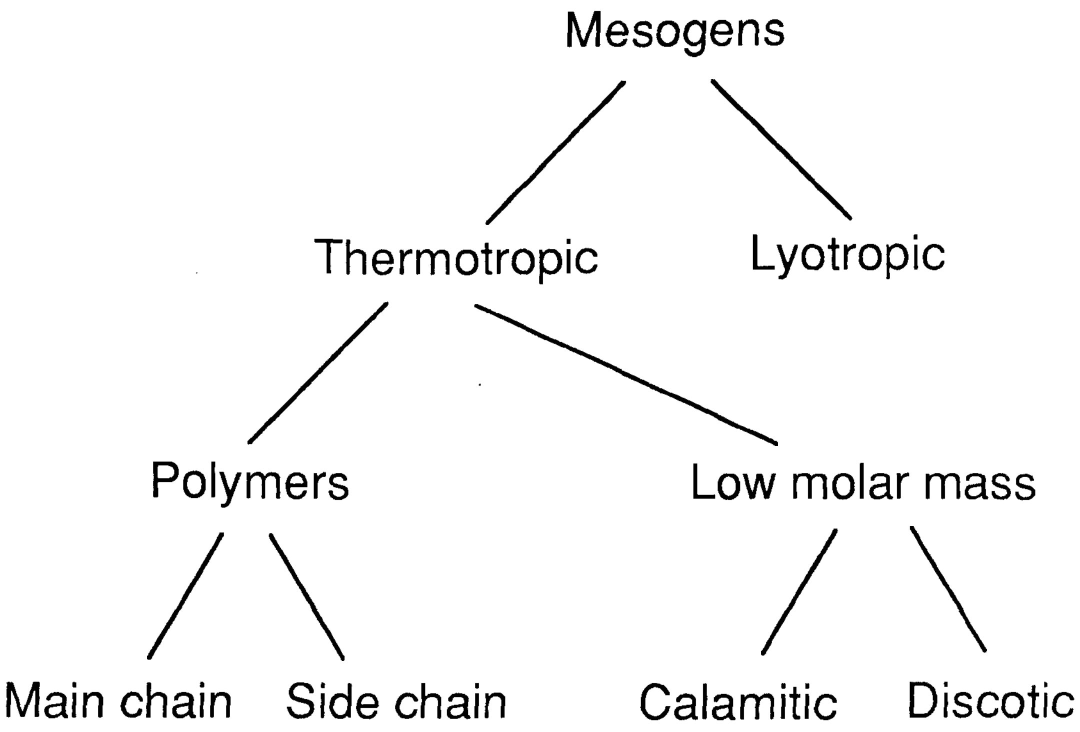
Mesogenic (*i.e.* mesophase-producing) compounds generally consist of long, narrow, lath-like and fairly rigid molecules (see Figure 1). In the crystal state (K), the molecules are held together by strong intermolecular forces of attraction which due to the lath-like structure are anisotropic (*i.e.* their magnitude will differ from one direction to another). In simple terms, the smectic phase arises if the lateral intermolecular forces of attraction are stronger than the terminal forces and so, on heating, the terminal forces breakdown first, in-plane translational order is lost and this results in a lamellar arrangement of molecules in which the layers can slide over each other (T2). Due to possible correlations within the layers and between the layers there are five smectic modifications and a further six *quasi*-smectic disordered crystal mesophases (see p 7). T3 illustrates the loss of both in-plane and out-of-plane translational order to leave a statistically parallel arrangement of molecules (orientational order) in the nematic phase. When the smectic phase is heated either out-of-plane translational ordering is lost (T4), which produces the nematic phase, or additionally orientational ordering is lost (T5), which gives the isotropic liquid. T6 represents the loss of orientational ordering of the nematic phase to give the isotropic liquid. The cholesteric phase simply represents the nematic phase for chiral molecules, but a racemic mixture will give a nematic phase.

An important feature of mesophase-mesophase and mesophase-isotropic liquid phase transitions is that they are exactly reversible (to within ~0.5 °C), whereas crystal-crystal, crystal-mesophase and crystal-isotropic liquid phase transitions are not because supercooling occurs. This can be useful in determining the presence of a mesophase and since supercooling occurs on cooling to the crystal state then mesophases may be revealed on cooling and not on heating. Such mesophases are called *monotropic* and the temperatures at which they occur are given in round brackets (). Monotropic mesophases always occur below the melting point, whereas mesophases which occur above the melting point are formed on both heating and cooling and are called *enantiotropic* mesophases.

Sometimes, compounds intended for possible use in liquid crystal mixtures will not be mesogenic. In order to determine how liquid crystalline such compounds are, a virtual (extrapolated) value is obtained but this process is usually only reliable for the nematic phase thermal stability. The procedure involves the mixing of the test compound in known compositions with a nematic host material of known T_{N-I} value. A graph is plotted of T_{N-I} value vs. transition temperature and the straight line is extrapolated to the composition point representing 100% of the test compound. The virtual T_{N-I} value is conventionally given in square brackets [].

1.3 Classification of Mesophases

Mesogenic materials are generally classified as shown in Figure 2.



Classification of Mesophases

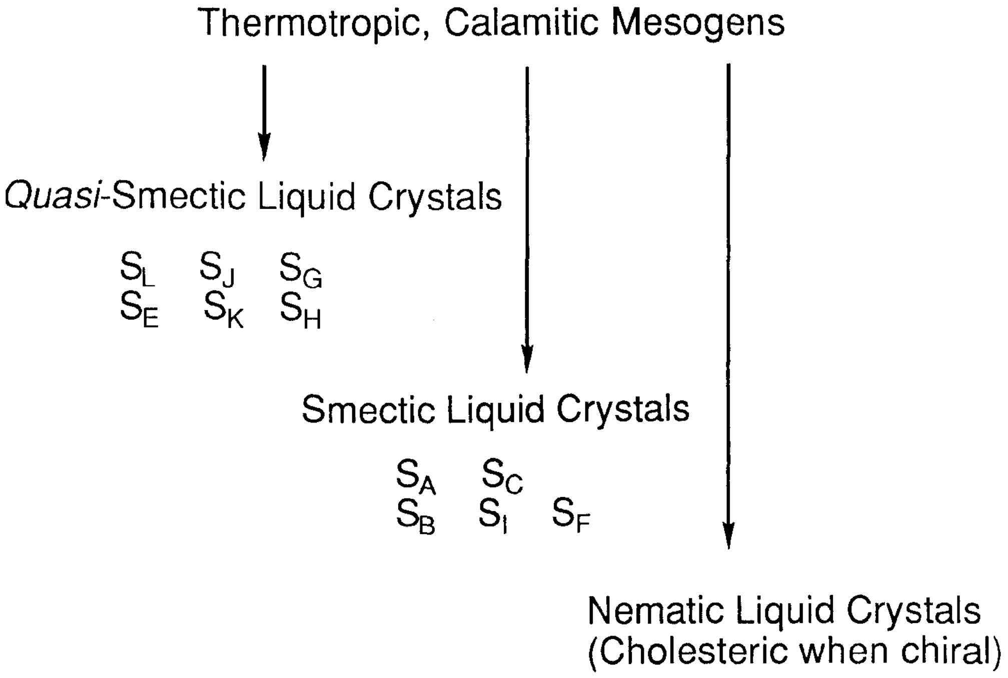
Figure 2

There are two main classes of mesophase:

(i) *thermotropic*, where mesophases are generated purely by heating or cooling;

(ii) *lyotropic*, where mesophases arise from the process of dissolution of an amphiphilic solid in a solvent (usually water).

Lyotropic,[14] polymeric,[15-18] and discotic[19,20] mesophases are beyond the scope of this thesis which is solely concerned with thermotropic, low relative molecular mass, calamitic mesogens[21-23] which are sub-divided into nematic liquid crystals[21-23] (cholesteric[24] for chiral molecules), smectic liquid crystals[13,25] and *quasi*-smectic disordered crystals[13,25] according to Figure 3.



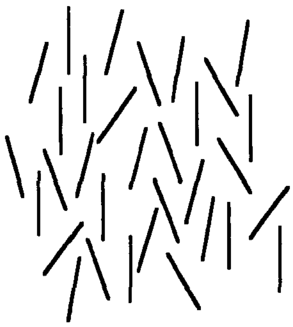
Classification of Calamitic Mesophases

Figure 3

1.3 (a) The Nematic Phase[21-23]

The nematic phase is the least ordered and technologically the most important liquid crystal phase due to its highly fluid nature. The nematic phase is a non-lamellar anisotropic liquid. The molecular positions show only short-range order in all directions but the molecules do possess *quasi*-long-range orientational order of their long molecular axes which takes the form of a statistically parallel arrangement of molecules (see Figure 4).

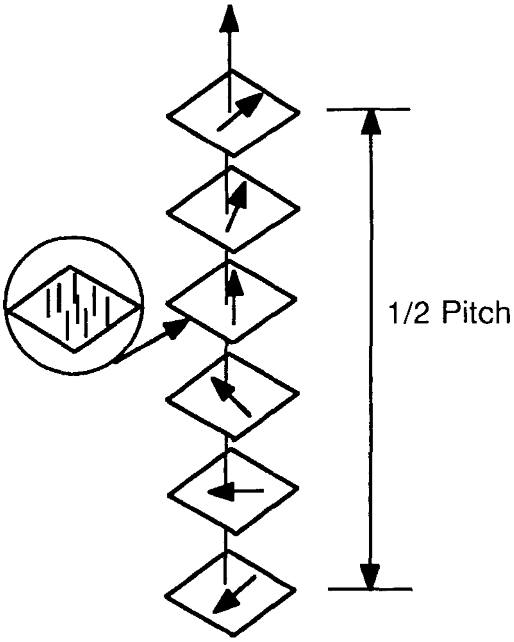
In 1927, Zocher[26] proposed the continuum theory of mesomorphic states which has been updated by Zocher[27] himself (1933), Oseen[28] (1933) and Frank[29] (1958). The continuum theory can be used to explain the existence and properties of the nematic phase and can be extended to include cholesteric and smectic mesophases. Maier and Saupe[30,31] reported the molecular statistical theory which suggests that the occurrence of mesophases is due to the anisotropy of molecular polarisability which is in turn determined by the molecular geometrical anisotropy.



The Molecular Arrangement of the Nematic Phase

Figure 4

1.3 (b) The Cholesteric Phase[24]



The Structure of the Cholesteric Phase

Figure 5

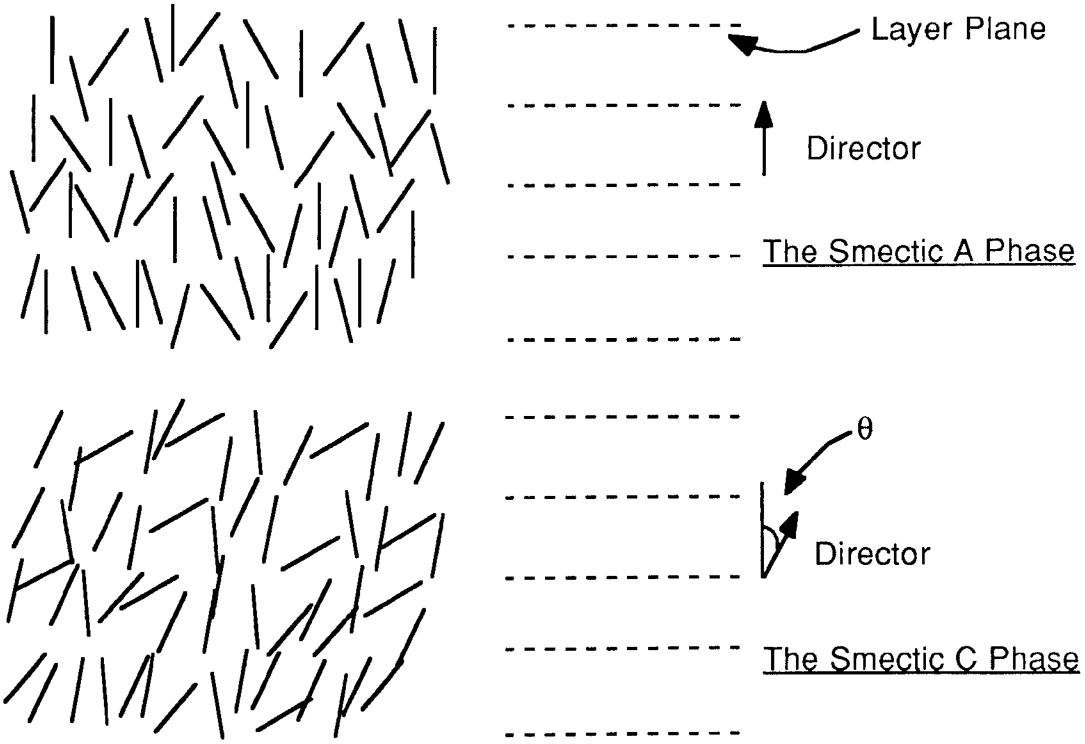
The cholesteric phase is a modification of the nematic phase and is exhibited only by compounds composed of optically active molecules. The racemic modifications of cholesterogens are known to exhibit nematic phases, but a slight excess of one optical isomer over the other will cause the mixture to become cholesteric. In fact, a nematic phase can be converted into a cholesteric phase by the addition of an optically active compound which need not be liquid crystalline.

The optic axis of a cholesteric material is orthogonal to the long molecular axis and so the cholesteric phase is optically of negative uniaxiality. The cholesteric phase is generally accepted as having a spontaneously twisted nematic structure (see Figure 5) and is often called the chiral nematic phase. The basic structure of the cholesteric phase can be envisaged as a sheet of molecules arranged horizontally, with their long molecular axes statistically parallel in the same direction. If the sheet immediately above is considered then these molecules will point in a slightly different direction which is skewed at a slight angle. The angle of rotation on passing to the adjacent sheet is small but the overall effect through successive sheets is to describe a helix (see Figure 5). The direction of rotation of the helix is opposite for each enantiomer and the length on going through 360° of the helix is called the pitch length. The helical structure is responsible for the unique optical properties of the cholesteric phase (see Applications of Liquid Crystals, p 23).

1.3 (c) The Smectic Phases and *quasi*-Smectic Disordered Crystal Phases[13,25]

When the smectic phase was first recognised by optical microscopy in 1917 by Grandjean[32] the sample (later shown to be S_A) showed stepped edges which indicated that the smectic phase was lamellar in nature.

The first point to deal with is the difference between the true smectic liquid crystal mesophases and the disordered crystal (*quasi*-smectic crystal) mesophases. The S_L, S_J, S_G, S_E, S_K and S_H phases are crystalline because of long-range positional order of the constituent molecules in three-dimensions and are often denoted by omitting the S and denoting them L, J, G, E, K and H because they are not smectic liquid crystals. However, these crystals do possess considerable disorder of molecular orientation and are therefore mesophases. In this thesis the S prefix has been retained in order to avoid confusing K (fully ordered crystal) with K (*quasi*-smectic, disordered crystal) and to avoid confusing the smectic (hexatic) B liquid crystal phase with the disordered crystal B mesophase, the latter has been denoted as L in the suffix (see Figure 3).



The Structure of the Smectic A and Smectic C Phases

Figure 6

The S_A and S_C phases are the least ordered of the smectic phases and they are both of technological importance in electrooptic display devices (see Applications of Liquid Crystals, p 23).

The S_A phase possesses *quasi*-long-range orientational order of the molecular long axes in one dimension in the same way as the nematic phase. However, the S_A phase has a distribution function which confers long-range positional order in one dimension which means the molecules are arranged in layers which are not well defined (see Figure 6). The S_C phase is the same as for the S_A phase except that the molecules are tilted in a preferred direction at an angle (θ) to the layer normal (see Figure 6).

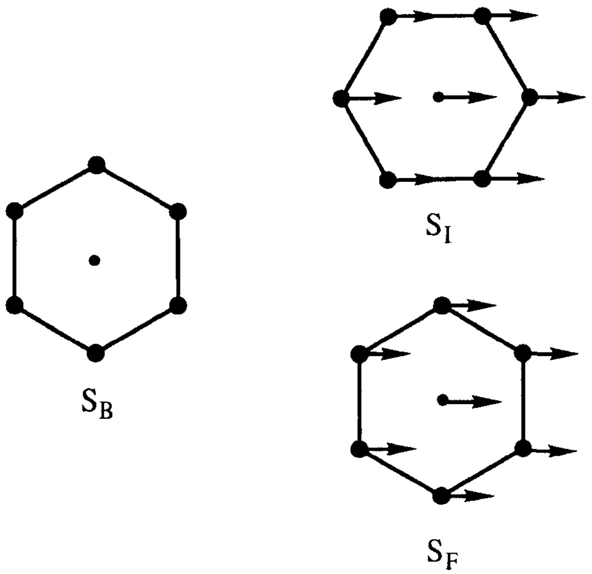
In many cases the presence of a strongly polar group (*e.g.* cyano) either in a pure compound or mixtures including such compounds confers additional ordering. This gives a tendency for the molecules to order themselves in a definite anti-parallel arrangement which leads to four 'different' types of S_A and S_C as follows:

S_{A1}, S_{C1}	conventional phases with completely random head-to-tail arrangements;
S_{A2}, S_{C2}	bilayer phase with head to head arrangements and a layer spacing of around 2x the molecular length;

S_{Ad}, S_{Cd}	semi-bilayers with an inter-digitated head-to-head arrangement and a layer spacing of around 1.5x the molecular length;
$S_{A\sim}$, $S_{C\sim}$	so-called antiphase behaviour with a modulated bilayer arrangement which gives a 'ribbon' structure.

The existence of these 'different' phases often leads to reentrant behaviour of phases giving sequences such as S_{A1}-N-S_{Ad}-N.

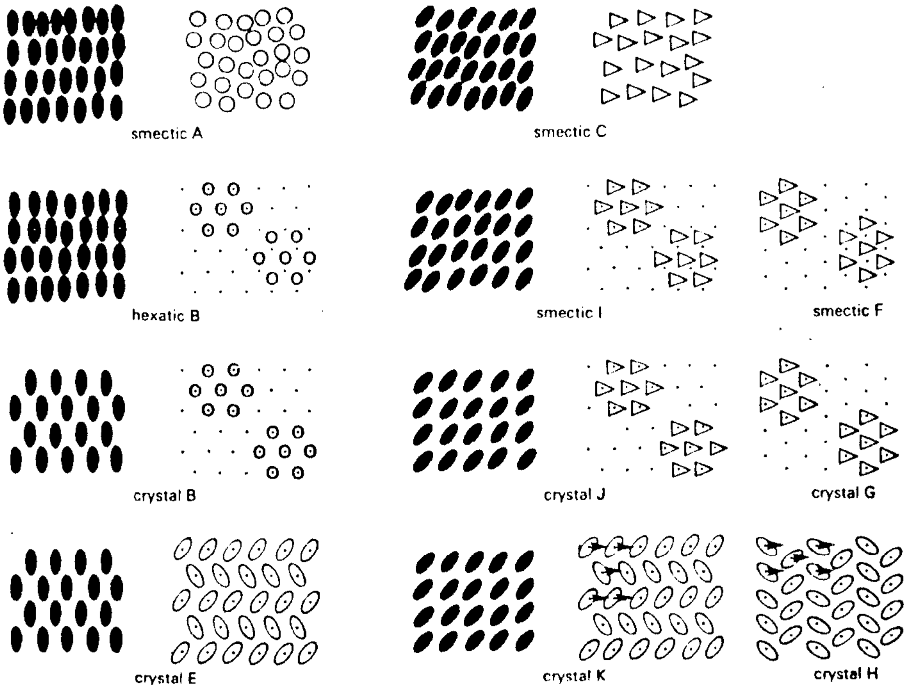
The S_B liquid crystal phase consists of hexagonal arrays which have a repeat positional order over ~150-600 Å (this is formally short-range positional order but is ~10x longer than for the S_A phase) within the layers. However, the hexagonal symmetry ('bond' orientational ordering) is found to be long-range in three dimensions. The S_I and S_F phases are as for the S_B phase except that the molecules are tilted at an angle (θ) to the layer normal. Due to the hexagonal symmetry this tilting can take two forms; if the hexagonal net tilts towards the apex then this gives the S_I phase, a tilt towards the edge of the hexagon produces the S_F phase (see Figure 7).



The Molecular Arrangement of the Smectic B, Smectic I and Smectic F Phases

Figure 7

The S_L crystal mesophase (often called the B phase) is directly derived from the S_B liquid crystal phase by the development of long-range positional order of the hexagonal arrays within the layers which necessarily brings long-range positional order between the



The Molecular Ordering in each of the Smectic Modifications

Figure 8

Figure 8 shows the excellent, concise summary (Gray and Goodby^{25}*) of the molecular ordering in each of the smectic modifications (crystal B is referred to as quasi-smectic L in this thesis). The blackened figures show the side elevation and the outlined figures represent a plan view. In the plan views, the circles and triangles represent rotational freedom of the molecules with triangles indicating the tilt direction. Ellipses represent the restricted rotation of molecules in a herringbone arrangement and if the molecules are tilted, then the tilt direction is shown by arrows. The points represent lattice positions for a crystalline solid.*

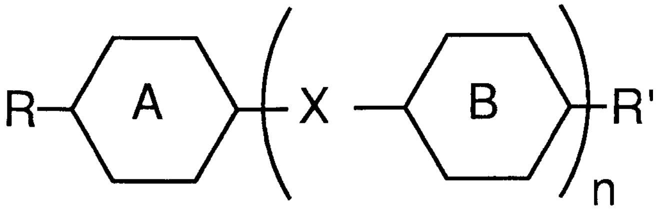
Clearly shown is the orthogonal nature of the S_A, S_B, S_L *and* S_E *mesophases and the tilted nature of the* S_C, S_I, S_F, S_J, S_G, S_K *and* S_H *mesophases. The plan views also show the hexagonal packing in the* S_B, S_I, S_F, S_L, S_J *and* S_G *mesophases and the herringbone packing arrangement of the molecules in the* S_E, S_K *and* S_H *mesophases.*

layers. The tilted S_J and S_G phases are similarly derived from the S_I and S_F phases respectively.

The highly ordered S_E phase and the tilted analogues S_K and S_H can be visualised as a contraction of the hexagonal net of the S_L phase and its tilted analogues S_J and S_G respectively. This contraction gives orthorhombic symmetry and a 'herringbone' packing arrangement which creates restricted rotation of the molecules. Two recent texts give excellent accounts of smectic mesophases.[13,25] The relative ordering of the various smectic and *quasi*-smectic mesophases are shown in Figure 8.[25]

1.4 Molecular Structure and Mesophase Thermal Stability[33-35]

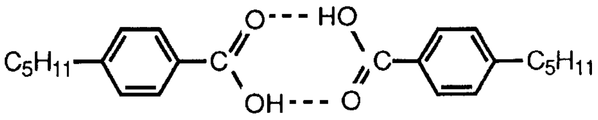
No really useful predictive method is available to relate molecular structure to mesophase type and thermal stability. However, a very large number of mesogenic materials have now been prepared which has led to many reviews on the subject. The structure of a mesogenic compound must be fairly rigid with a lath-like shape and most mesogenic compounds are covered by the general formula below (Figure 9).



A General Formula for Mesogenic Materials

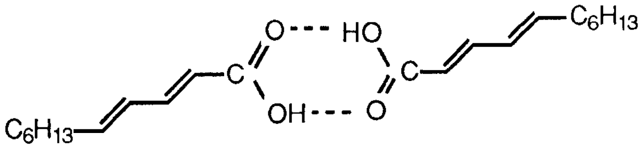
Figure 9

A and B are rings which provide the main core of the structure which may be extended by the use of a linking group (X) and R and R' represent the terminal substituents. At least two rings are normally required to stabilize a calamitic liquid crystal phase except for compounds which dimerise to achieve liquid crystal phase thermal stability (*e.g.* compound I). Compound II represents a genuinely acyclic mesogen, examples of which are extremely rare.



(I)

K 88.0 N 126.5 I

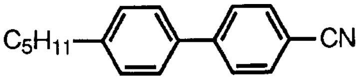


(II)

K 32.0 N 62.5 I

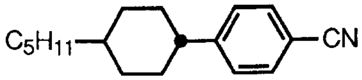
Aromatic rings are most common in mesogenic systems due to their relative ease of synthesis but cyclohexane and bicyclo[2.2.2]octane rings support mesophase thermal stability to a greater extent (compare compounds III, IV and V).

(III)



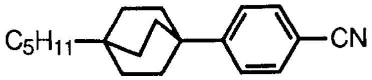
N-I = 35.0 °C

(IV)



N-I = 55.0 °C

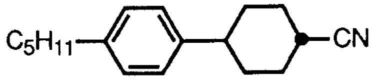
(V)



N-I = 100.0 °C

Systems including aromatic and alicyclic rings are possible but regions of high polarisability should not be separated by non-polar regions. Compound (VI), for example, has the aromatic ring separated from the cyano-substituent by a cyclohexane ring with the consequence of a very low $T_{N\text{-}I}$ value.

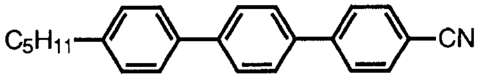
(VI)



N-I = (-25.0 °C)

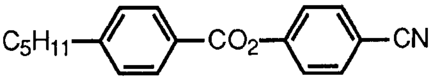
The mesophase thermal stability is raised by extending the core system by the use of extra rings (compound VII) or by the use of a suitable linking group which maintains the rigidity and linearity of the molecule (compounds VIII and IX). However, the breaking up of polarisability by a linking group dramatically reduces the $T_{N\text{-}I}$ value (compound X).

(VII)



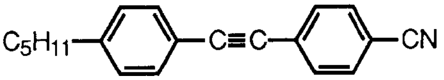
N-I = 239.0 °C

(VIII)



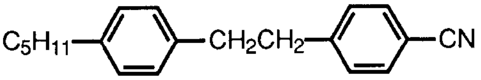
N-I = 55.5 °C

(IX)



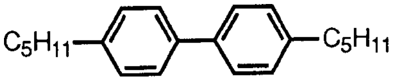
N-I = 70.5 °C

(X)



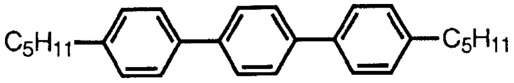
N-I = [-24.0 °C]

The choice of terminal substituent has a crucial effect on mesophase type and thermal stability. Generally one polar terminal group (*e.g.* cyano) will produce nematic phases (compound VII) but as the alkyl or alkoxy chain length increases then a smectic phase eventually replaces the nematic phase (see Material Requirements for the Smectic A Display Devices, p 48). Where both terminal groups are alkyl or alkoxy then such non-polar compounds tend to be highly smectic in character (compounds XI and **296**).



(XI)

K 26.0 S_B 47.6 S_A 52.2 I



(296)

K 192.0 S_A 213.0 I

The efficiency order of terminal groups for promoting nematic phase thermal stability has been found to be as follows:

$Ph > NHCOCH_3 > CN > OCH_3 > NO_2 > Cl > Br > N(CH_3)_2 > CH_3 > F > H$.

Broadening the core by lateral substitution generally depresses nematic phase thermal stability in proportion to the size of the substituent but independent of its polarity and if the lateral substituent causes a steric effect (*i.e.* an inter-annular twist) then mesophase thermal stability is depressed even more. Generally, lateral substitution will depress smectic phase thermal stability more than nematic phase thermal stability, perhaps because the substituent affects the lamellar packing. However, if the lateral substituent is highly polar then this polarity, to some extent, counteracts the size effect and helps to support the smectic phase.

A lateral fluoro-substituent is frequently used in liquid crystal compounds to modify their physical properties. The fluoro-substituent is so useful for this purpose because of its very high electronegativity and its very small size. In many cases a lateral fluoro-substituent enables melting points to be reduced considerably and eliminates undesirable smectic phases from mixtures used in the nematic-based display devices (see also Material Requirements for Display Devices, p 45). A lateral fluoro-substituent *ortho* to a terminal cyano-substituent tends to break up antiparallel correlations and create compounds with higher positive dielectric anisotropy values whereas compounds of negative dielectric anisotropy can be obtained by the use of lateral fluoro-substituents. Compounds with lateral substituents are a large feature of this thesis and therefore further discussion is found in Sections 1 and 2 of the Results and Discussion (p 237 and p 262). Two notable texts exist which list the transition temperatures of many mesogenic compounds.[36,37]

1.5 Physical Properties of Nematogens

The nematic phase has received the most attention as regards to physical property measurements and this is because the physical properties of nematogens have major consequences for their use in display devices. The physical properties discussed below can, however, be applied to other liquid crystal phases.

1.5 (a) Order Parameter

It was mentioned earlier that the constituent molecules of the nematic phase align, on average, parallel to one another but that there is considerable disorder of molecular orientation (see Figure 4, p 6). The order parameter, S, is a measure of the microscopic local ordering that exists within the system and is a measure of the efficiency of the molecules to align parallel to the nematic director (n); it is defined by Equation 1, where θ

$$S = 0.5 < 3 \cos^2\theta - 1 > \qquad (1)$$

is the angle between the director (n) and the long molecular axis and < > imply a space-time average over a large number of molecules. For a perfectly crystalline solid, θ is zero and so $S = 1$, for the isotropic liquid phase $S = 0$. For nematics, typical values for S are in the range 0.4 to 0.7.

1.5 (b) Optical Properties

The anisotropic nature of liquid crystals gives rise to interesting optical properties. The most important optical property of liquid crystals is that of double refraction (birefringence). The refractive indices of nematic liquid crystals may be measured by using an Abbe refractometer where the nematic director is perpendicular to the direction of propagation of the light beam. Under these circumstances an incident light beam will be split into an ordinary and an extraordinary ray polarised respectively perpendicular and parallel to the nematic director (n). The two rays are deflected through different angles and travel at different velocities. The optical anisotropy is the difference between the two refractive indices (Equation 2).

$$\Delta n = n_{||} - n_{\perp} \qquad (2)$$

In nematic and smectic liquid crystals the director is always parallel or nearly parallel to the optic axis of the phase; this presents an easy pathway for propagation of polarised light and so $n_{||} > n_{\perp}$ and Δn is always positive. In the cholesteric phase the director is perpendicular to the optic axis, and so the two refractive indices are almost equal ($n_{||} \leq n_{\perp}$) and Δn is negative.

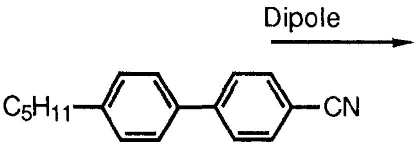
On a molecular level, the refractive indices are determined by the electronic polarisability. Consequently, nematic liquid crystals consisting of aromatic rings (especially when conjugated with other moieties of high polarisability, for example an alkoxy terminal chain or an ethynyl linking group) tend to give high values of Δn (as high as ~0.45). Values of Δn close to zero can be achieved by avoiding the use of groups of high polarisability and by using saturated alicyclic rings.

1.5 (c) Dielectric Anisotropy

The anisotropy of dielectric constants in the nematic phase mirrors that of the refractive indices. The dielectric anisotropy ($\Delta\varepsilon$) of liquid crystals is defined as the difference between the dielectric permittivity values measured parallel ($\varepsilon_{||}$) and perpendicular ($\varepsilon_{\perp}$) to the director (n) according to Equation (3).

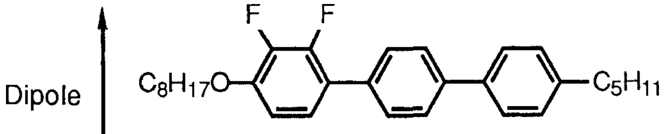
$$\Delta\varepsilon = \varepsilon_{||} - \varepsilon_{\perp} \qquad (3)$$

The nematic director (n) tends to orientate itself parallel (positive $\Delta\varepsilon$) or perpendicular (negative $\Delta\varepsilon$) to the electric field (E) and the sign and magnitude of the dielectric anisotropies are dependent on the strength and orientation of any dipole moments.



(III)

$\Delta\varepsilon = +12$



(160)

$\Delta\varepsilon = -4.2$

The dielectric anisotropy ($\Delta\varepsilon$) is proportional to the square of the dipole moment (D) (Equation 4). Compound III exhibits positive dielectric anisotropy and compound **160** is of negative dielectric anisotropy.

$$\Delta\varepsilon \propto D^2 \qquad (4)$$

Positive and negative dielectric anisotropies are discussed further on p 254 and p 298 respectively.

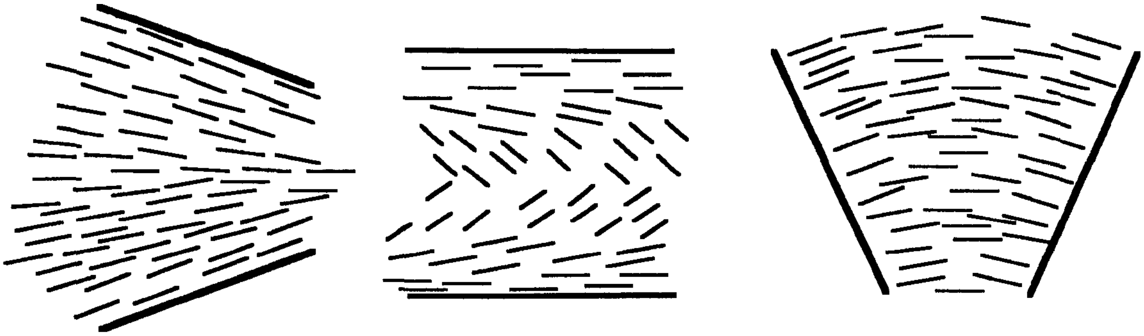
A high positive dielectric anisotropy is a desirable feature of nematic mixtures used in the twisted nematic display device because this reduces the threshold voltage (V_C) as given in Equation 5.

$$V_C = \pi \left(\frac{k_{11} + (k_{33} - 2k_{22}) / 4}{\varepsilon_0 \, \Delta\varepsilon} \right)^{1/2} \qquad (5)$$

Where k_{11}, k_{22}, k_{33} are the elastic constants associated with splay, twist and bend deformations respectively (see p 16) and ε_0 is the dielectric permittivity of free space. However, since a low $\Delta\varepsilon / \varepsilon_{\perp}$ is essential for a good threshold sharpness and good multiplexing performance, the optimum values of $\Delta\varepsilon$ are between 2.5 and 5.0.

1.5 (d) Elastic Constants

Liquid crystals are unique among fluids in their elastic behaviour. Since liquid crystals are fluids a static shear stress is impossible but it is possible for liquid crystals to transmit a torque stress.



Splay, k_{11} Twist, k_{22} Bend, k_{33}

The Splay, Twist and Bend Deformations of the Nematic Phase

Figure 10

Ideally, the molecules in the nematic phase orientate themselves in a preferred direction of lowest energy to minimise elastic torque. The distortion of this state requires energy but even in the absence of external forces, boundary conditions can provoke configurational deformations. Three types of distortion are possible in the nematic liquid crystal phase, these are splay, twist and bend (see Figure 10) and these distortions are opposed by the corresponding elastic constants, k_{11}, k_{22}, k_{33} respectively.

$$T_{ON} = \frac{\gamma_1}{\varepsilon_0 \Delta\varepsilon E^2 - K \pi^2 / d^2} \qquad (6)$$

$$T_{OFF} = \frac{\gamma_1 d^2}{K \pi^2} \qquad (7)$$

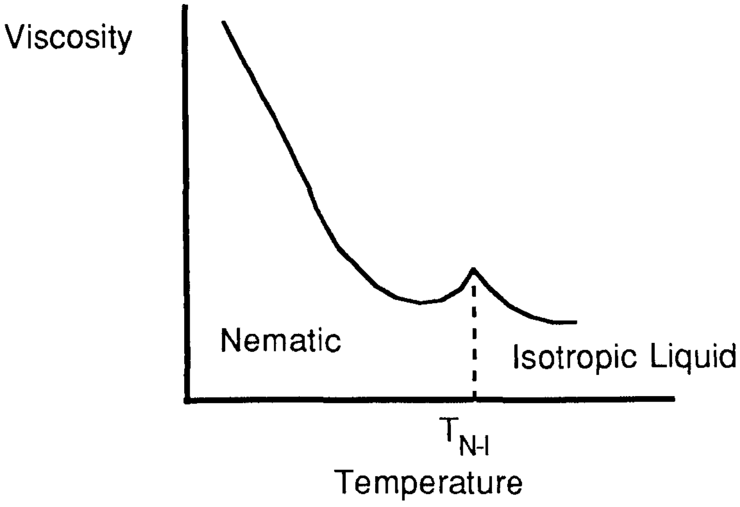
$$V_S \propto \frac{1}{\frac{k_{33}}{k_{11}} + \frac{\Delta\varepsilon}{\varepsilon_\perp}} \qquad (8)$$

Where γ_1 is the twist viscosity, E is the applied electric field, K is an average of the elastic constants and d is the cell thickness.

The elastic constants (or their ratios) are important to the reponse times and the sharpness of the threshold voltage (V_S) of the twisted nematic display device (Equations 6, 7 and 8). It can be seen that low values of K are required for fast response times and that a low value of k_{33} / k_{11} is essential for good threshold sharpness and good multiplexing performance.

1.5 (e) Viscosity

The viscosity of a nematic material is strongly affected by temperature (see Figure 11). As the T_{N-I} transition is approached on heating there is a large increase in viscosity which peaks at the T_{N-I} value. If the nematic and isotropic liquid regions of the plot are extrapolated, it is seen that the nematic viscosity is lower than the viscosity of the isotropic liquid. This is not surprising since the molecules of a nematic phase are aligned parallel in flow fields giving better flow characteristics than for the randomly arranged molecules in the isotropic liquid phase. As can be seen from Equations 6 and 7, a low viscosity in a nematic mixture is essential for fast response times in the twisted nematic display device. The viscosity of the nematic phase is much lower than the viscosity of smectic liquid crystal mesophases and the nematic phase is therefore much better suited for display device use which involves the movement of the molecules to produce an optical effect.



The Effect of Temperature on the Viscosity of a Nematic Liquid Crystal

Figure 11

1.6 Identification of Mesophase Type

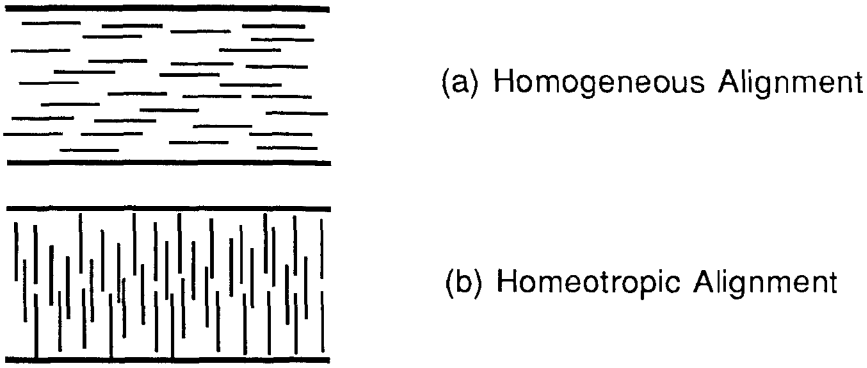
The nematic phase and its chiral analogue the cholesteric phase are the least ordered mesophases and their identification is quite simple. However, in recent years the study of smectic liquid crystals (and *quasi*-smectic crystals) has grown in complexity. For positive identification of some smectic materials it is essential to use a combination of several techniques. These include optical microscopy, thermal analysis, miscibility studies and X-ray diffraction. However, for most purposes the combination of optical microscopy and thermal analysis is sufficient for the experienced worker to identify the mesophase types.

1.6 (a) Optical Microscopy (see also photomicrographs, p 319)

Optical microscopy is the first line in mesophase identification and is a very important tool. Major contributions in the identification of smectic phase types by polarising microscopy have been made by Sackmann and Demus[38,39] and Gray *et al.*[25,40]

A thin film of material on a microscope slide gives a characteristic texture when viewed between crossed polarisers. Each mesophase type has its own distinctive texture or textures which arise from the different molecular organisation of the material. A texture developed from cooling of the isotropic liquid is termed a natural texture, whereas a texture derived from the cooling of another mesophase type is called a paramorphotic texture.

The nematic phase is very fluid and this aids microscopic identification; dust particles within the sample are seen to undergo intense Brownian motion and when the coverslip is displaced (which is very easy) the sample will shimmer. Perhaps the most characteristic feature of the nematic liquid crystal phase is the way it develops on cooling the isotropic liquid phase. Spherical birefringent droplets appear against a black background of the optically extinct isotropic liquid phase (see Plate 1). As the temperature falls these droplets coalesce rapidly to give a texture which depends on the thickness of the sample and the nature of the supporting surfaces. The highly coloured homogeneous texture results when attractive forces with the glass are strong. If the sample is thick then a threaded texture is formed on cooling the isotropic liquid and when most of the sample is homeotropic a marbled texture may be seen. The schlieren texture (see Plate 2) is produced near the T_{N-I} value and is a highly birefringent texture which consists of distorted crosses with either 2 or 4 black bands, called brushes, emerging from the centre.



Possible Molecular Alignment in the Nematic Phase

Figure 12

For these birefringent textures, the molecular alignment is homogeneous [see Figure 12 (a)]. The homeotropic texture results from homeotropic alignment [see Figure 12 (b)] and because the light shines down the optic axis of the molecules then this texture is optically extinct (this texture is also seen for the orthogonal smectic mesophases when the molecules are similarly aligned).

By using certain techniques uniform alignment of a sample is possible and these alignment orientations may be interchanged by the application of an electric field which is the basis behind electro-optic display devices (see Applications of Liquid Crystals, p 23). A polyimide layer rubbed in a unidirectional manner for example gives a uniform homogeneous alignment. Homeotropic alignment is achieved by using very clean glass surfaces or by using a thin coating of lecithin or dimethylpolysiloxane.

Plate 3 shows the appearance of batonnet on cooling to the S_A phase which on further cooling coalesce to give a focal conic fan texture (Plate 4). The cholesteric phase exhibits two distinctive textures by optical microscopy; these are called the focal conic fan texture and the Grandjean planar texture (see Plates 5 and 6). The textures of blue phases[41-43] which sometimes appear between the cholesteric phase and the isotropic liquid phase for cholesteric materials of short pitch are beyond the scope of this thesis.

The identification of smectic liquid crystal and *quasi*-smectic crystal mesophases by optical microscopy without experience is difficult but it is possible in some cases. However, in many cases it is virtually impossible for all but the most experienced workers to determine beyond doubt the identity of the mesophase. In many cases textures of the smectic phases are very similar (in fact almost identical) which makes identification difficult when using conventional glass slides and coverslips. However, a technique using a free-standing film[44] can greatly aid mesophase identification. This involves the pulling of a thin film of S_A or S_C material over a hole in an aluminium plate. When viewed under a polarising microscope this technique works very well for identifying tilted smectic mesophases. Orthogonal mesophases appear black due to homeotropic alignment of the molecules (*i.e.* the layers are suspended across the hole in the plate).

The subject of smectic textures is excellently covered in a recent text[25] and therefore the following discussion is based on the author's experience of compounds covered in this thesis only. By using a free standing film the S_A phase is orthogonal and so appears black, an underlying S_C phase (see Plate 7) will appear as a schlieren texture which is very sharp and highly birefringent. Many areas of extinction appear as four black brushes (schlieren brushes) which meet at a point of singularity (a point of singularity is clearly seen in Plate 8) (in nematics either two or four brushes are possible). If an S_I phase (see Plate 9) appears below the S_C phase then this will be very similar to the S_C texture (both schlieren). However, the S_I phase is clearly difficult to focus on and has a dull appearance. A free-standing film gives such an excellent view of a texture that the S_I phase can be distinguished from the normally very similar S_F phase. The schlieren texture of an S_F phase has mosaic boundaries (the compounds covered by this thesis do not exhibit the S_F mesophase). When using conventional glass slides for smectic phase identification it is beneficial to obtain the S_A phase with focal conic fans and homeotropic texture in the same region. This enables the underlying S_C phase to be seen as broken fans and schlieren textures respectively (see Plates 11 and 12), although an underlying S_I phase will be difficult to detect.

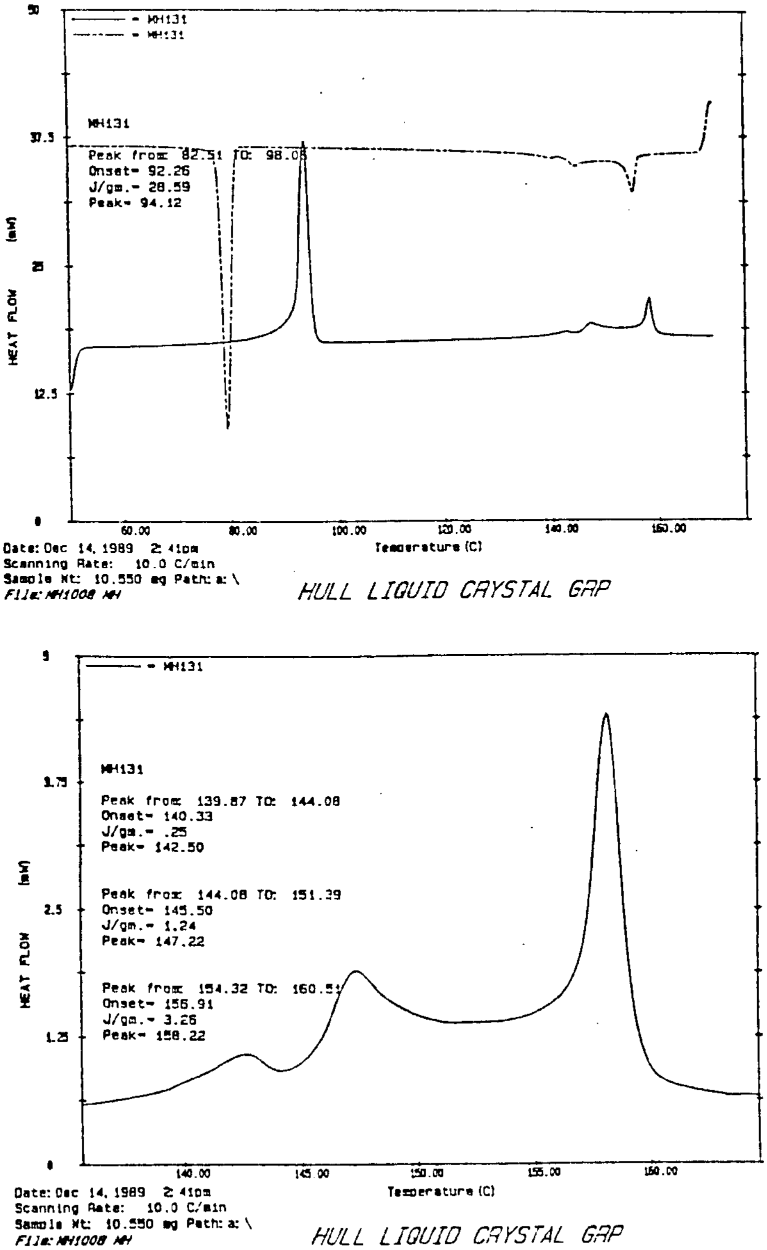
Several compounds prepared for this thesis show an S_G mesophase below either an S_A, S_C or an S_L mesophase. By using the free-standing film technique, the S_G mesophase appears as the growth of dendrites from the periphery to the centre of the film over the black homeotropic texture (S_A or S_L) or the birefringent schlieren texture (S_C). The dendrites grow and eventually form the mosaic texture (see Plate 10). The S_J mesophase, however, does not grow dendritically but grows as rounded mosaics which are less crystalline than for the S_G mesophase with a few lines appearing within the mosaics.

An S_B or an S_L phase is very difficult to detect when appearing below an S_A phase because the textures are virtually identical but changes in the appearance of the fans at the transition temperature may enable the underlying S_B or S_L phase to be identified. At the S_A to S_L transition, transition bars appear across the fans and then disappear on further cooling. At the S_A to S_B transition, no transition bars are seen, instead there is a slight change in the birefringence colour and in the radial lines of the fans. The S_B and the S_L mesophases are distinguishable by the shapes of the focal-conic fan domains. For the S_L phase, the domains are angular, instead of curved, because the S_L phase has long-range molecular ordering in three dimensions and so the layers are not curved or bent easily.

1.6 (b) Thermal Analysis[45]

Differential scanning calorimetry (DSC) uses resistive heaters to determine the energy input to (or taken from) the sample to maintain isothermal conditions between the sample and the reference (Al_2O_3). On heating and cooling of the sample, phase transitions are accompanied by an enthalpy change and the DSC instrument records this enthalpy change as a peak. The temperature at which the peak occurs is the phase transition temperature and the area underneath the peak represents the enthalpy change. Mesophase detection is possible because all transitions between mesophase and mesophase or between mesophase and the isotropic liquid phase are reversible. Therefore, by performing a heating and a cooling cycle the reversible peaks can be attributed to mesophases. DSC analysis simply reveals the presence of a mesophase at a particular temperature and gives the enthalpy change of the transition; it does not enable the direct identification of mesophase type. However, the magnitude of the enthalpy change can sometimes provide information as to the phase type involved.

When smectic phases which are difficult to detect by optical microscopy are involved, their presence can be initially revealed by DSC analysis which 'pin-points' the temperature ranges of the mesophases. Once the temperature at which the mesophase



Typical DSC Traces for the Heating and Cooling of Compound **160**

Figure 13

Figure 13 shows typical DSC traces for compound ***160****. The upper figure gives the cooling trace (dashed line) above the heating trace, an arrangement which clearly shows the mesophase - mesophase and mesophase - isotropic liquid transitions to be reversible. The lower figure shows an expansion of the* S_C - S_A, S_A *- N and N - I transition peaks. The enthalpy change associated with each transition is given which illustrates the very small enthalpy change for the* S_C - S_A *transition.*

exists is known then a more detailed examination by optical microscopy can be made close to the transition temperatures.

The enthalpy changes occuring at transition temperatures are often useful in phase identification. Transitions to and from the S_L and S_B phase are usually characterised by large enthalpy changes (~4-8 kJ mol^{-1}) and are first order transitions, however, transitions to the S_B phase may be second order in nature. The transition of the S_A phase to the isotropic phase or the nematic phase is usually accompanied by an enthalpy change of ~4-6 kJ mol^{-1}. The nematic or S_A phase transitions to the S_C phase often show a very small enthalpy change (<1 kJ mol^{-1}) and sometimes an S_C to S_A transition will be undetected by even the most sensitive of instruments. However, such transitions are easy to detect by simple optical microscopy. For compounds prepared for this thesis, the S_C to S_A transitions gave extremely small enthalpy changes but in most cases they were detected by the DSC instrument; the S_C to nematic transitions were always detected. Typical DSC heating and cooling traces for a compound showing the phase sequence K - S_C - S_A - N - I are shown in Figure 13.

1.6 (c) Miscibility Studies

Earlier, it was stated that it is often difficult to distinguish between the various types of *quasi*-smectic and smectic mesophases. Sackmann and Demus[39] have shown that the various types of smectoid mesophases can be classified by the concept of continuous miscibility between identical mesophases. The method depends on the fact that complete miscibility of two mesophases over the entire composition range is only possible if both phases have the same structure. However, the test is one of miscibility not immiscibility and so if two mesophases are not miscible it does not necessarily mean that they are not of the same mesophase type.

This technique works well for the nematic mesophase and orthogonal smectoid mesophases, but these are easily identified by using optical microscopy. Tilted smectoid mesophases, which are most difficult to identify by using optical microscopy cannot be as reliably assigned as orthogonal mesophases by miscibility studies.

In some cases two compounds mixed together may give a smectic phase which is not exhibited by either of the two pure compounds, such phases are called injected phases. In some other cases, both the compounds may exhibit a smectic phase which disappears for certain compositions of the binary mixture.

Therefore, this technique requires the use of a wide range of compounds and a lot of experience.

1.6 (d) X-ray Diffraction

This technique has been applied to liquid crystals since 1923[46] and is the ultimate in mesophase type identification as it actually provides structural information of the phase. The results can be used to determine the tilt angle for tilted mesophases, the molecular length and the layer spacing.

The diffraction pattern of the nematic phase usually consists of a diffuse inner-ring, corresponding to the molecular length and the minimal order in the direction of the molecular long axes. In contrast, X-ray diffraction patterns for smectic phases show a sharp inner-ring which is indicative of a periodic layer structure; the outer ring or rings give information about the molecular arrangement within the smectoid layers.[47,48] X-ray diffraction studies on carefully aligned samples provided the evidence that the S_L, S_J, S_G, S_E, S_K and S_H mesophases are not liquid crystalline but are true crystals which possess considerable disorder of molecular orientation.[25]

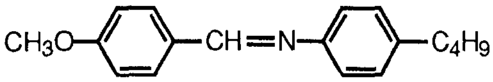
A combination of these identification techniques has been used to classify smectic and *quasi*-smectic mesophases into the correct group; most notably the distinction between the hexatic B (S_B) and the crystal B (S_L)[49,50] and the classification of the tilted phases into miscibility groups with standard nomenclature.[25,51-55] The most probable order of thermal stability for smectic mesophases has been reported[56] to be as follows:

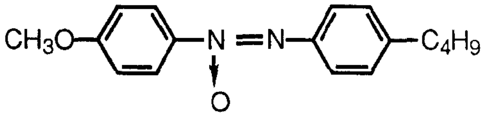
K S_H S_K S_E S_G S_J S_F S_L S_I S_B S_C S_A I.

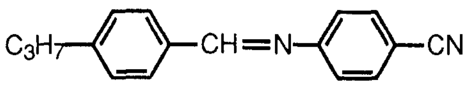
1.7 Applications of Liquid Crystals

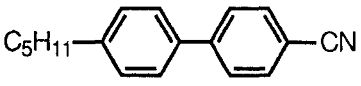
1.7 (a) Display Devices

Liquid crystals are fluids in which, due to partial orientational ordering of the constituent molecules, the material properties such as permittivity and refractive index are anisotropic; because of this, their potential for use in flat-panel electronic displays has been known for a long time. In the 1960s, compounds incorporating a conjugating linking-group between aromatic systems were thought to be essential for liquid crystallinity.


(XII)
K 22.0 N 47.0 I


(XIII)
K 43.0 N 76.0 I


(XIV)
K 46.0 N 62.0 I

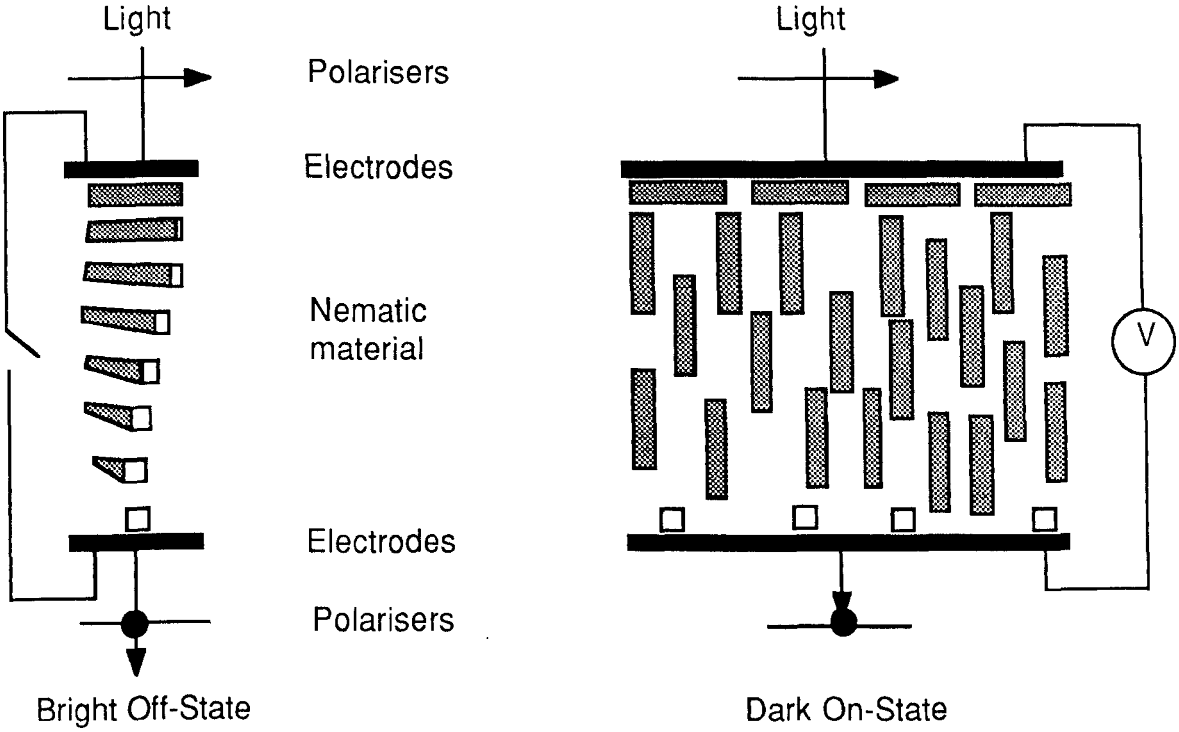

(III)
K 22.5 N 35.0 I

Compounds XII and XIII gave room temperature nematic liquid crystal mixtures which were used to demonstrate dynamic scattering [Heilmeier[7,8] (1968)] and so showed the potential of nematic liquid crystals for display device purposes. However, high voltages and high power consumption were disadvantages of the dynamic scattering devices and when the twisted nematic display device[10] was demonstrated using compound XIV interest in liquid cyrstal displays became very intense. Since compounds XII, XIII and XIV are either coloured, or are photochemically or hydrolytically unstable, the chemical research centred around the development of chemically stable nematic liquid crystal materials of positive dielectric anisotropy which could be used to formulate a room temperature nematic mixture. In 1973 Gray *et al.*[11,12] discovered the cyanobiphenyl class of compound (III) by removing the linking group in compounds of type XIV. This was the most important breakthrough in the history of liquid crystals as it provided the material with which to realise a marketable nematic liquid crystal display device and also it stimulated a lot of research and development into the wider field of liquid crystals.

Today, almost all liquid crystal display devices are still based on the nematic phase. This is because of the wide availability of suitable nematic materials and the fact that the nematic phase is more fluid and therefore inherently less viscous than other mesophases.

This gives low power consumption, which is less than 1 μW cm^{-2} for the twisted nematic display devices, making them ideal for battery-powered, portable applications which are generally operated at low drive voltages (3-5 V). Modern displays incorporate advanced nematic liquid crystal material mixtures which have excellent physical properties and a wide operating temperature range to suit their application and they are inherently long lived and offer exceptional reliability. Being essentially a passive, light modulating (as opposed to light emitting) device, liquid crystal displays give excellent performance in high ambient lighting. Also, because of the diversity of this flat-format device and its high reliability, the liquid crystal display device is increasingly being used in situations where back-lighting is required. Display devices based on the smectic A and smectic C phases have also been developed; the ferroelectric display device based on the chiral smectic C (S_C*) phase is an extremely important development and will be discussed in detail later (see p 38).

1.7 (a) (i) Nematic Phase Display Devices



The Operation of the Twisted Nematic Display Device

Figure 14

The *Twisted Nematic Display Device*[10] (see Figure 14) consists of two parallel glass plates spaced ~5-10 μm apart, the gap being filled with a nematic liquid crystal. Each

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glass plate carries a transparent, electrically conducting layer [indium oxide and tin oxide (ITO)] which is etched to leave the switchable areas of the display. The surfaces are then coated with a special molecular orientation layer (usually polyimide) which is rubbed with nylon or velvet in a unidirectional manner and the nematic molecules align parallel to this direction and are inclined slightly to the glass plate. This inclination angle is called the 'surface tilt angle' or 'pretilt angle and is usually ~1-3°. The rubbing directions of the upper and lower glass plates are arranged mutually perpendicular and because of the fluid nature of the nematic phase a 90° twist of the nematic director is induced over the cell thickness. The twist direction is ensured by a very small amount of a chiral dopant[57] which prevents the formation of opposing twist senses which otherwise often occur in this device. The cell is placed between crossed-polarisers which are parallel to the rubbing direction (and therefore to the nematic director). The plane of polarised light entering the cell will be guided through 90° by the twisted nematic liquid crystal material if the product of birefringence (Δn) and cell spacing (d) is large compared with half the wavelength of the incident light; this condition is known as the Mauguin limit.[58] For values of Δn x d of greater than 1 μm, the light guiding properties of the cell are almost independent of cell thickness and most twisted nematic devices are constructed to this specification. However, for some displays intended for applications where a wide angle of view is important (*e.g.* in TFT active-matrix-driven twisted nematic devices, see p 32), the cells are constructed with a Δn x d value of ~0.48 μm which is referred to as a 'first minimum' display[59,60] and a good appearance is dependent on the accurate control of the cell thickness. Light is able to pass through the lower polariser and therefore in the 'off-state' the cell appears bright. Applying an electric field ('on-state') *via* the ITO electrodes, the molecules tend to align parallel to the electric field (except for a monolayer which is held by surface forces) and so destroy the twist (see Figure 14). They do this because they are of positive dielectric anisotropy (*i.e.* $\varepsilon_{\parallel} > \varepsilon_{\perp}$) due to the net terminal dipole of the molecules (*e.g.* cyanobiphenyls). In this 'on-state' the polarisation of the incident light remains unchanged throughout the cell and the light is consequently absorbed in the second (crossed) polariser, giving the dark 'on-state'. The use of two parallel polarisers instead of crossed ones gives

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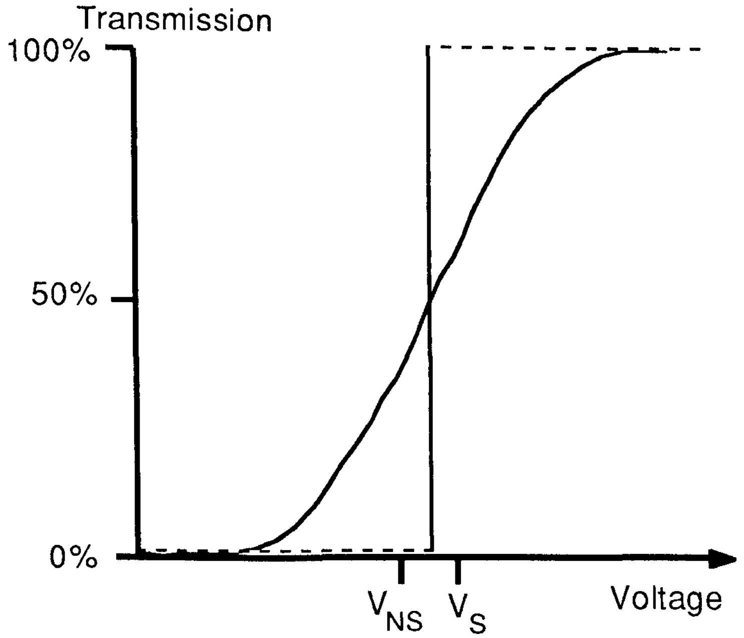
a dark 'off-state' and a bright 'on-state'. The critical voltage (V_C) required to produce the reorientation effect is given by Equation 5,

$$V_C = \pi \left(\frac{k_{11} + (k_{33} - 2k_{22}) / 4}{\varepsilon_0 \, \Delta\varepsilon} \right)^{1/2} \qquad (5)$$

were k_{11}, k_{22} and k_{33} are the elastic constants which measure the stiffness of the director against splay, twist and bend deformations respectively (see p 16); $\Delta\varepsilon = \varepsilon_{\|} - \varepsilon_{\perp}$, where $\varepsilon_{\|}$ and $\varepsilon_{\perp}$ are the permittivities measured parallel and perpendicular to the nematic director respectively (see p 14), and ε_0 is the permittivity of free space. When the field is removed the surface forces (aided by the monolayer next to the surface) restore the original twisted conformation of the 'off-state'.

In order to develop the discussion of display applications further it is necessary to discuss the methods of addressing displays. The simplest type of method is *Direct (Static) Addressing* which involves individual connections for each pixel and, because of the bulk and intricacy of the display caused by this, only the most simple displays can be addressed directly. This direct drive is, however, advantageous in that it has a broad temperature range, little dependence on the angle of view, short switching times and little sensitivity to fluctuations in the addressing voltage. The obvious drawback is that the number of connections is very large even for a simple display. A dot-matrix display of N rows and M columns would need N x M connections for N x M pixels. To solve this problem the pixels are addressed by the *Time Multiplex Process (Multiplex Addressing)*[61-63] which requires only N + M connections and the individual segments are addressed by means of suitably staggered signals. For a twisted nematic device the transmission (or extinction) versus voltage curve is rather flat (see Figure 15). This is no problem for direct addressing as the 'off-voltage' can be zero and the 'on-voltage' can be several times the threshold voltage (V_C). However, for multiplex addressing this flat curve (see Figure 15) is a problem.



The Flat Electrooptic Characteristic of the Twisted Nematic Display Device and an Ideal Electrooptic Characteristic Shown by a Dashed Line

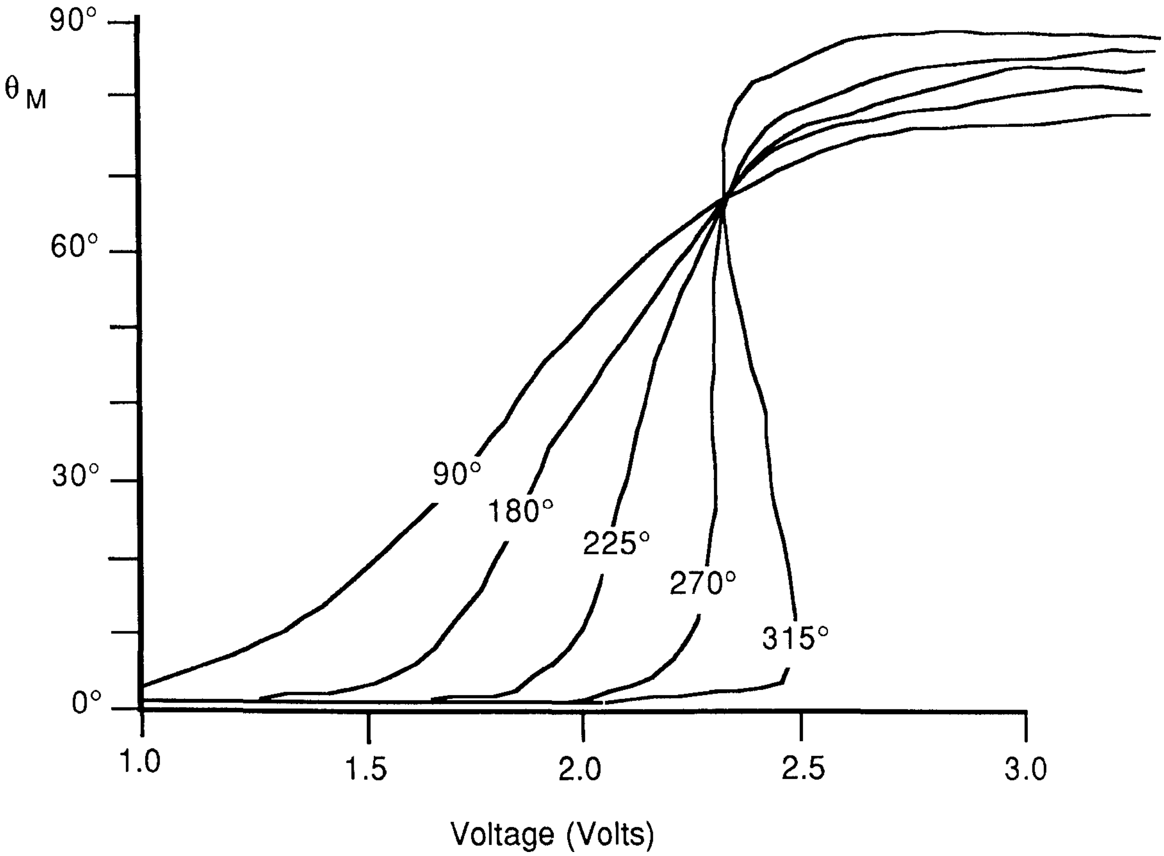
Figure 15

The 'off-voltage' is now termed the non-select voltage (V_{NS}) and the 'on-voltage' is called the select voltage (V_S). The ratio V_S / V_{NS} has been derived by Alt and Pleshko[61] and is given by Equation 9,

$$V_S / V_{NS} = [(N^{0.5} + 1) / (N^{0.5} - 1)]^{0.5} \qquad (9)$$

where N is the maximum number of addressable rows. So when the device consists of 100 rows the difference between V_S and V_{NS} is only 11% and with a flat electrooptical characteristic the pixels will never be completely on or off. Therefore, in order to use multiplex addressing for a display of even a moderate number of rows without compromising the contrast, the electrooptical characteristic must be of nearly infinite slope (*i.e.* very steep, see dashed line in Figure 15). Although steeper electrooptical curves can be obtained by optimising dielectric properties, elastic constants and optical path difference (Δn x d), multiplex addressed twisted nematic devices of good contrast are limited to ~ 32 rows.

In order to develop liquid crystal displays with higher information content (larger displays) it is necessary to either change the addressing system (see active matrix addressing, p 32) or use a different electrooptic effect. In 1982 Raynes *et al.*[64] reported



The Electrooptic Characteristic for Various Degrees of Twist

in Twisted Nematic and Supertwisted Nematic Display Devices

Figure 16

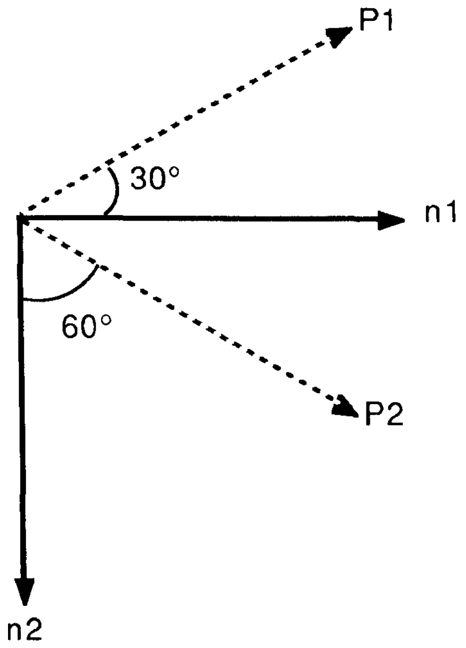
that more tightly twisted configurations have a sharper threshold. A twist angle of 270° gives an electrooptical characteristic with infinite slope. Such devices with twist angles of greater than 90° are termed *Supertwisted Nematic Liquid Crystal Display Devices*. Such large twist angles can be achieved by adding large amounts of a chiral (not necessarily liquid crystalline) dopant (as opposed to the small amount added to the twisted nematic device, see p 26); a twist angle of 270° is obtained for a cell spacing (d) to pitch (p) ratio of 0.75.

Figure 16 shows the change in electrooptical characteristic as a function of twist angle [note: Figure 16 shows the tilt angle in the middle of the layer (θ_M) as a function of the applied voltage rather than % transmission (Figure 15)]. A twist angle of 270° represents an optimum infinite threshold slope and beyond this the slope shows hysteresis (*i.e.* bistability).[65,66]

The first supertwisted nematic devices were based on the guest-host mode of operation[67,68] (see p 34), but it was quickly realised that a two-polariser mode similar to that of the twisted nematic device was preferable and this became known as the *Supertwisted Birefringent Effect.*[69-71] Since the twist angle is higher than for the twisted nematic device, the guiding of the light is imperfect (it is not totally perfect for the twisted nematic device) and so the optical effect is very much an interference effect between the ordinary and the extraordinary rays. This means that the cell thickness must be constant within a tolerance of ±0.1 μm. Depending on material and cell parameters, the supertwisted birefringence effect can be obtained from twist angles of between 180 and 270°. The 270° twist gives the best angle of view and due to a steeper electrooptical characteristic enables better multiplexability. However, with such a tight twist a pretilt angle of at least 5° is required if the formation of scattering effects due to other director configurations of similar free energy is to be avoided. Such large pretilt angles could only be obtained by oblique evaporation of SiO, a technology incompatible with modern liquid crystal display device mass production, and so most supertwisted birefringence effect devices have twist angles of between 180 and 240°. However, new polyimides have been developed which by standard rubbing techniques enable pretilt angles of up to 10° to be achieved and this should permit the mass production of better supertwisted birefringent effect display devices.

The construction of the supertwisted birefringent effect display is very similar to the twisted nematic device (see Figure 14), although stricter manufacturing tolerances are required. Assuming a twist of 270°, the rubbing directions (n1 and n2) (see Figure 17) are mutually perpendicular (as for the twisted nematic device). Placing one polariser (P2) at 60° to the rubbing direction of one plate and the other polariser (P1) at 30° to the rubbing direction of the other plate allows the positive contrast 'yellow mode' to be obtained (dark blue/black figures on a yellow background). By rotating one polariser through 90° the negative contrast 'blue mode' is obtained (white/grey figures on a blue background).

These supertwisted birefringent effect devices have the distinct disadvantage of being coloured. Although multi-coloured displays are desirable, it is advantageous to have a black and white display and then any colour can be achieved by the use of coloured



The Polarisers and Molecular Directions for The Supertwisted Nematic Display

Figure 17

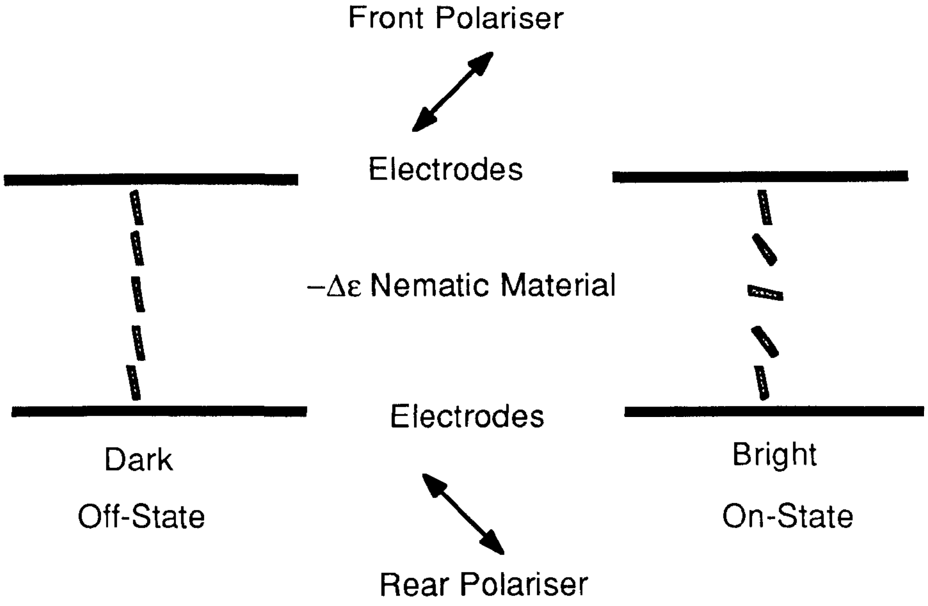
filters. The much sharper threshold curve of the supertwist device means that the whole curve lies closer to the threshold voltage (V_C) than for the twisted nematic device and the phenomenon of 'critical slowing down' in the region close to V_C leads to the supertwisted device having inherently slower response times than for the twisted nematic device; a further disadvantage is the need to make cells with very accurately defined and uniform thickness. The supertwisted birefringent effect device does have the advantage of being highly multiplexable at high contrast and has a good angle of view, but even these devices have limits on size and the maximum so far produced has been 400 x 640 pixels.

In 1987 Leenhouts and Schadt[72] reported the development of a supertwisted nematic device which gave the desired neutral black and white appearance and was called an *Optical Mode Interference Device* (OMI). For normal supertwisted nematic devices (SBE) the optical path difference ($\Delta n \times d$) is adjusted to be between 0.8 and 1.0 μm but the reduced optical path difference of between 0.4 and 0.6 μm and the small wavelength dependence on transmission for the OMI device are responsible for its neutral black and white appearance. The small dependence of wavelength on transmission means that cell spacing and birefringence need not be so closely controlled as in a standard supertwisted nematic device and this makes production easier; however, OMI devices have the disadvantage of poor brightness (less than half the brightness of a standard supertwisted nematic device). The OMI device has a twist angle of 180° with one polariser in line with the nematic director and the other at 45°.

Standard supertwisted nematic devices can be made to give a perfectly neutral black and white appearance and this is achieved by placing a second (colour-compensating) cell between the active display cell and the front polariser.[73] The compensating cell does not need electrodes because it is not switched but it clearly adds to the cost of the display and its fabrication occupies production capacity. The second cell has the same magnitude but the opposite sense of twist to the active cell and this means that the optical path difference ($\Delta n \times d$) of the compensating cell cancels that of the active cell giving an effective optical path difference of zero; the system therefore has no birefringence and gives the desired neutral black and white appearance. These devices are termed *Double Layer Black and White Supertwisted Nematic* (DST) and are already commercially available and are much brighter than the OMI device but also more expensive.

For applications requiring a very large number of pixels (100000 to 1232640, *i.e.*, 250x400 to 960x1284) and a fast response time (*e.g.* colour televisions up to 14 inch diagonal) then the limitations of multiplex addressed supertwisted nematic devices are revealed. A form of addressing called *Active-matrix Addressing*[74] has been developed where a non-linear switching element is integrated into each picture element (pixel). The non-linear switching element can either be a two-terminal device like a diode or MIM (metal-insulator-metal), or a three terminal device such as a TFT (thin-film transistor); TFTs offer the best performance but are more expensive. The use of an active non-linear switching element, brings us back to a situation we had for the directly addressed twisted nematic device and so the voltage levels in the select and non-select states are no longer restricted and so the performance of a TFT-addressed twisted nematic device does not deteriorate with an increasing number of pixels, in contrast to multiplex addressed devices. The active-matrix system can be used to drive a variety of liquid crystal display devices but most attention has been devoted to twisted nematic devices. Active-matrix addressed twisted nematic devices are invariably used for colour televisions with colour being introduced by the use of (red, green and blue) colour filters located on the inner surface of the non-active-matrix plate of the cell, under the ITO electrode layer. Such colour displays require grey-scale and this is why a flat electrooptical characteristic is preferred (this contrasts with the steep electrooptical characteristic required by a mutiplex addressed device). TFT-addressed twisted nematic devices operate in the 'first minimum'[59,60] which means that the optical path difference (Δn x d) is adjusted to ~0.48 μm which gives a wide angle of view; such devices offer good contrast, full colour and a fast response time. Liquid crystal materials for this device are required to have a high resistivity and to be of low birefringence and the device needs to be strongly back-lit since, due to the combination of colour filters and polarisers, as little as 5% of the luminous energy is transmitted. A 14 inch diagonal colour television display with 960 x 1284 pixels has been publicly demonstrated and 5 inch devices are now on sale. TFTs offer the best overall performance currently available and are expected to develop quickly into big selling devices as airline companies are already installing these devices into the backs of aircraft seats for the entertainment and business requirements of passengers.

Another nematic liquid crystal display device, called the *Electrically Controlled Birefringence* device (ECB) was first described in 1971[75-77] but could not compete with the twisted nematic device. The ECB device needs homeotropic surface alignment and the nematic liquid crystal mixture must have negative dielectric anisotropy and both these conditions have been difficult to achieve in the past. The operating principles of the ECB device are shown in Figure 18. The homeotropically aligned 'off-state' has no birefringence (light is shining down the optic axis) and so when viewed in conjunction with crossed-polarisers, a dark appearance results. When the applied voltage exceeds V_C then, because the molecules are of negative dielectric anisotropy, the homeotropic configuration is distorted to a tilted 'on-state' which is now birefringent and light can be transmitted; the small pretilt angle of 1° ensures a uniform switching. A small variation in the applied voltage generates a significant change in transmission; the resulting steep electrooptical characteristic means that the ECB device can cope with high multiplex ratios.[78-80] The smaller the pretilt angle the steeper the threshold, but pretilt angles of less than 0.5° lead to



The Operation of The Electrically Controlled Birefringence Display

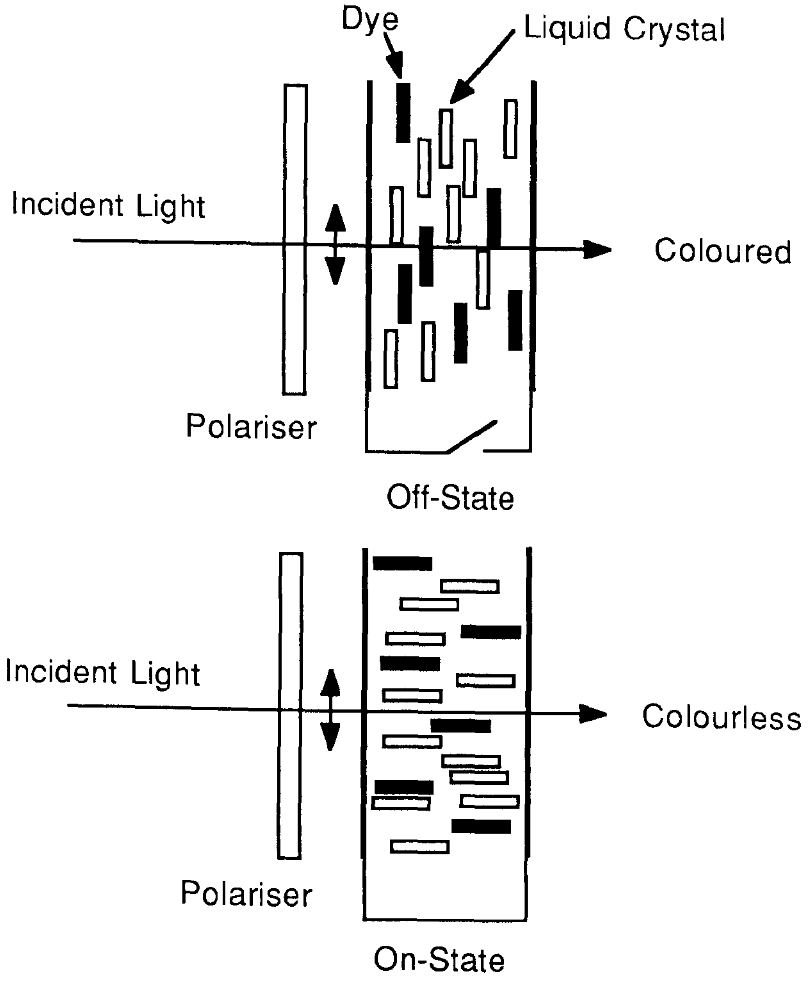
Figure 18

the appearance of inversion walls; a large optical path difference (Δn x d) also gives a steeper electrooptical characteristic. In order to obtain the steep electrooptical characteristic required for high multiplex ratios, combined with fast response times and a wide viewing angle, the following are required: a thin cell (d<5 μm), a small pretilt angle (0.5-1.0°), a large optical path difference (Δn x d ~1.0 μm), a large ratio of k_{33}/k_{11} (>1.5) and a small $|\Delta\varepsilon| / \varepsilon_{||}$ (<0.5).

The expense of polarisers and the loss of brightness resulting from their use combined with the black and white nature of the twisted nematic display device has led to the development of *Guest-Host* displays.[81-84] Liquid crystal materials have the property of being able to align rod-shaped solute molecules which do not themselves show mesophases. This guest-host effect of the nematic phase has been exploited for a solute which is a dye. In dichroic (anisotropic) dyes the absorbance (A) will be different for light polarised parallel ($A_{||}$) and perpendicular ($A_{\perp}$) to the transition moment director and an optical order parameter is defined by Equation 10.

$$S_{Op} = (A_{||} - A_{\perp}) / (A_{||} + 2A_{\perp}) \qquad (10)$$

Dichroic dyes for use in nematic mixtures for guest-host diplays must have a large S_{Op} (~0.8), have a high absorption coefficient, have high solubility, be stable, pure and of high resistivity. Azo dyes tend to offer better order parameters, larger extinction coefficients and better solubility in nematic mixtures, whereas anthraquinone materials generally have better photochemical stability.



The Operation of The Single Polariser Guest-Host Display Device

Figure 19

In *Single Polariser Guest-Host* devices[81] (see Figure 19) the director is electrically switched between configurations in which plane polarised light propagating through the cell experiences either $A_{||}$ or $A_{\perp}$. In the original homogeneous alignment ('off-state') the dye molecules cause the polarised light to be coloured due to absorbance. However, when the nematic mixture is of positive dielectric anisotropy and a voltage is applied, the alignment becomes homeotropic and the dye molecules do not absorb light and so a colourless appearance occurs. The effect will also work for a twisted nematic device in which the polariser is aligned parallel to one of the rubbing directions. It should be noted that the cell has to be homeotropically aligned throughout the whole of the cell and this means that higher voltages have to be used than for the twisted nematic device. This device cannot be multiplex addressed because of its flat electrooptic characteristic.

Single polariser guest-host devices have found successful use in public information displays (at railway stations, airports and stock exchange dealing halls). These types of display are made up in dot matrix format but they are so large that individual connections for direct drive is not a problem and neither are the higher voltages because the displays need to be back-lit. Low maintenance costs, high reliability, elimination of one polariser, good angle of view and a bright appearance are the advantages of this display.

Another guest-host display which avoids the need for polarisers altogether is called the *Dyed Phase-Change* device[84] which involves doping the guest-host mixture with cholesteric material; there are also versions of this device and of the single polariser guest-host device which use fluorescent dyes but none of these will be discussed in this thesis.

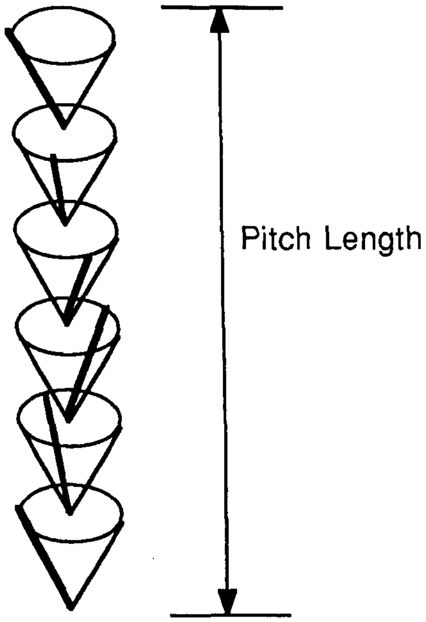
1.7 (a) (ii) Smectic Phase Display Devices

The use of even the least ordered smectic phases (A and C) in display devices has been restricted by their high viscosity relative to that of the nematic phase. The high viscosity means that dielectric coupling of the phase requires a large field strength in order to bring about an orientational effect although a device based on the S_C* phase is being developed which looks very promising and it will be discussed in detail later. The first display device based on smectic materials was reported by Kahn[85] in 1973. Two types of display device based on the S_A phase have been developed and although not relevant to any compounds prepared for this thesis a brief discussion is still thought to be important.

Both the S_A devices work on the principle of switching between the optically extinct homeotropic alignment and the focal conic texture which contains a multiplicity of small domains where the director orientation varies rapidly and therefore scatters light strongly. The *Thermally Addressed Smectic A* device[86,87] consists of homeotropically aligned S_A material of positive dielectric anisotropy which gives a transparent 'off state' (which appears black due to a black backplate). A low powered, computer-controlled laser beam is used to heat an area into the isotropic phase through a small-range nematic phase, and when the beam passes on the written areas cool and the S_A phase is regenerated in the thermodynamically stable, light-scattering focal conic texture. This gives white information on a black background which can be stored for any length of time without additional energy expenditure. The stored information can be selectively erased by rewriting the data in the presence of an electric field (cooling now regenerates the homeotropic S_A texture); total erasure is achieved by heating the whole cell above the $T_{N\text{-}I}$ value and cooling with an electric field applied. This device gives a bright display of high resolution with built-in memory; the information can be projected onto a large area screen. There are, however, problems associated with temperature control and slow writing times.

The *Electrically Addressed Smectic A* device was developed by Crossland and Ayliffe[88] and is very similar to that described above except that the homeotropically aligned S_A phase is doped with ionic material so that when a low frequency voltage (50-80 V) is applied, electrohydrodynamic turbulence occurs giving the light-scattering focal conic texture. Dyes may be added to enhance the scattering effect and to add colour. When a high frequency signal is applied the effect is reversed, due to the positive dielectric anisotropy of the S_A material. The sharp threshold characteristic for the scattering voltage combined with the memory make high level multiplex addressed, large flat-panel displays possible; the image quality is excellent and there is no viewing angle limitation. High voltages mean it cannot be used in portable equipment but it can easily compete with monochrome cathode ray tube (CRT) displays and has the advantage of having better image quality, flat-format and on-screen memory.

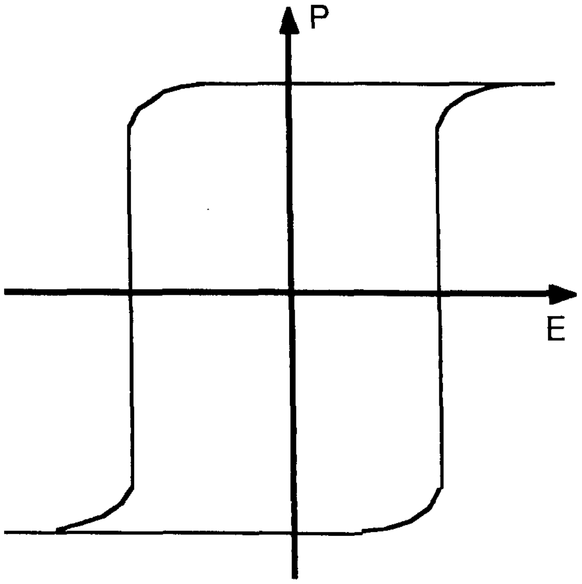
The *Ferroelectric (Chiral Smectic C)* display device is so called because of the nature of the chiral smectic C (S_C*) mixture used in the device.[89-92] The S_C phase has a structure in which the constituent molecules are arranged in layers and are tilted at a temperature dependent angle [$\theta(T)$] with respect to the layer normal. For a chiral smectic C (S_C*) phase the molecular tilt direction changes slightly on going through the layers, eventually describing a helix (see Figure 20) which is analogous to the helix given by the cholesteric phase (see Figure 5, p 5). A material is termed ferroelectric if, in the



The Helical Structure of The Chiral Smectic C Phase

Figure 20

absence of an applied field, it possesses two or more orientational states, and by applying an electric field it can be switched from one of these orientational states to another. Should the material be capable of retaining these orientational states in the absence of an applied field this means that the device is bistable.[93,94]

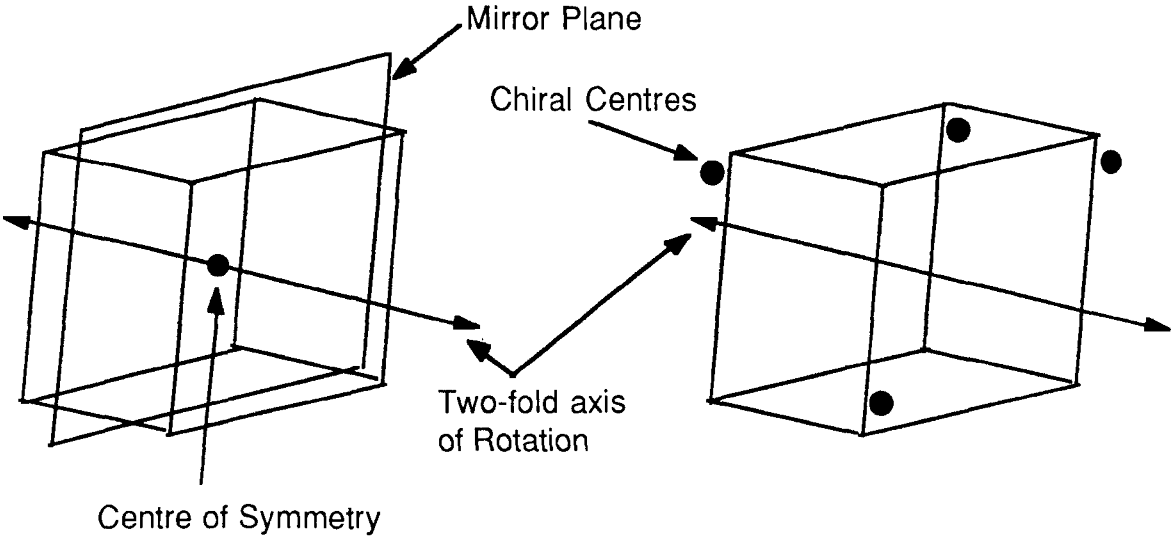


The Bistable Nature of The Chiral Smectic C Phase

Figure 21

The relationship between polarisation (P) and electric field (E) for a ferroelectric mixture (see Figure 21) clearly shows its bistable nature in the form of a hysteresis loop. It is from this loop that the spontaneous polarisation (P_S) of the mixture can be measured.

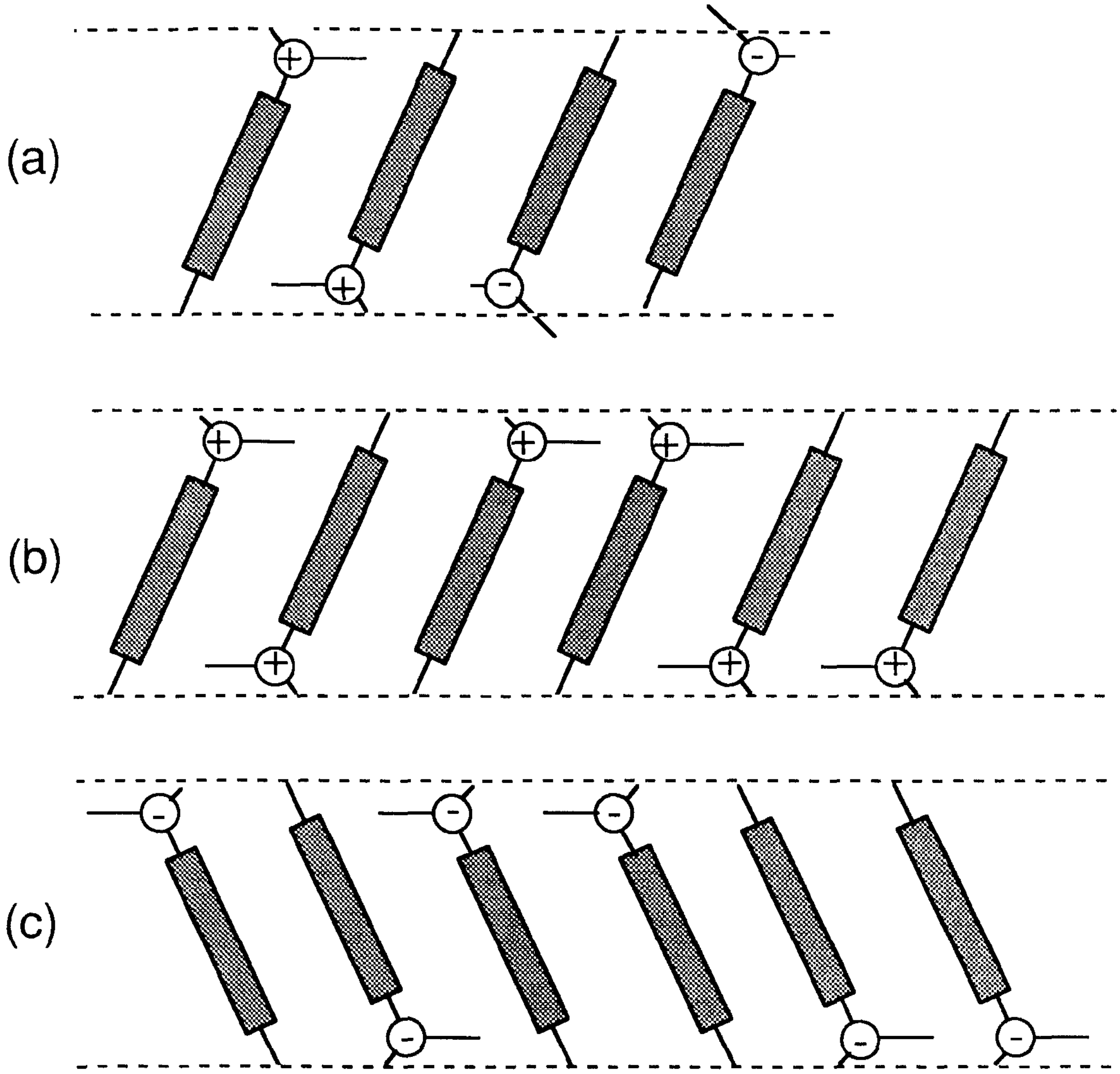
Of fundamental importance for ferroelectric behaviour is the symmetry of the 'unit cell' (the unit cell being part of a single smectic layer). Ferroelectric properties can only arise if the unit cell is of low symmetry *e.g.* monoclinic or orthorhombic, where a centre of symmetry is absent (see Figure 22). The presence of a centre of symmetry means that a dipole in any direction will always be cancelled by an equal and opposite polarisation. The tilted achiral S_C phase possesses three elements of symmetry: (i) a two-fold axis of rotation (normal to the tilt axis), (ii) a mirror plane (in the plane of the tilt axis) and (iii) a centre of symmetry. However, when the molecules are chiral the mirror plane and the centre of symmetry have disappeared and the only element of symmetry present is the polar two-fold axis of rotation (see Figure 22). Symmetry considerations led Meyer *et al.*[95] (1975) to establish that ferroelectric properties could be exhibited by the low symmetry, chiral smectic C phase (S_C*).



The Symmetry of The Non-Chiral and Chiral Smectic C Phases

Figure 22

A system has been proposed by Raynes[96] to explain why the two orientational states exist in the S_C* phase. Figure 23 (a) shows the four possible tilted orientations of a chiral molecule and illustrates that only molecules of like-polarisation can align within the constraints of the layer when all are tilted in the same direction (as in the smectic C phase).



The Molecular Arrangement Within The Layers of The Chiral Smectic C Phase

Figure 23

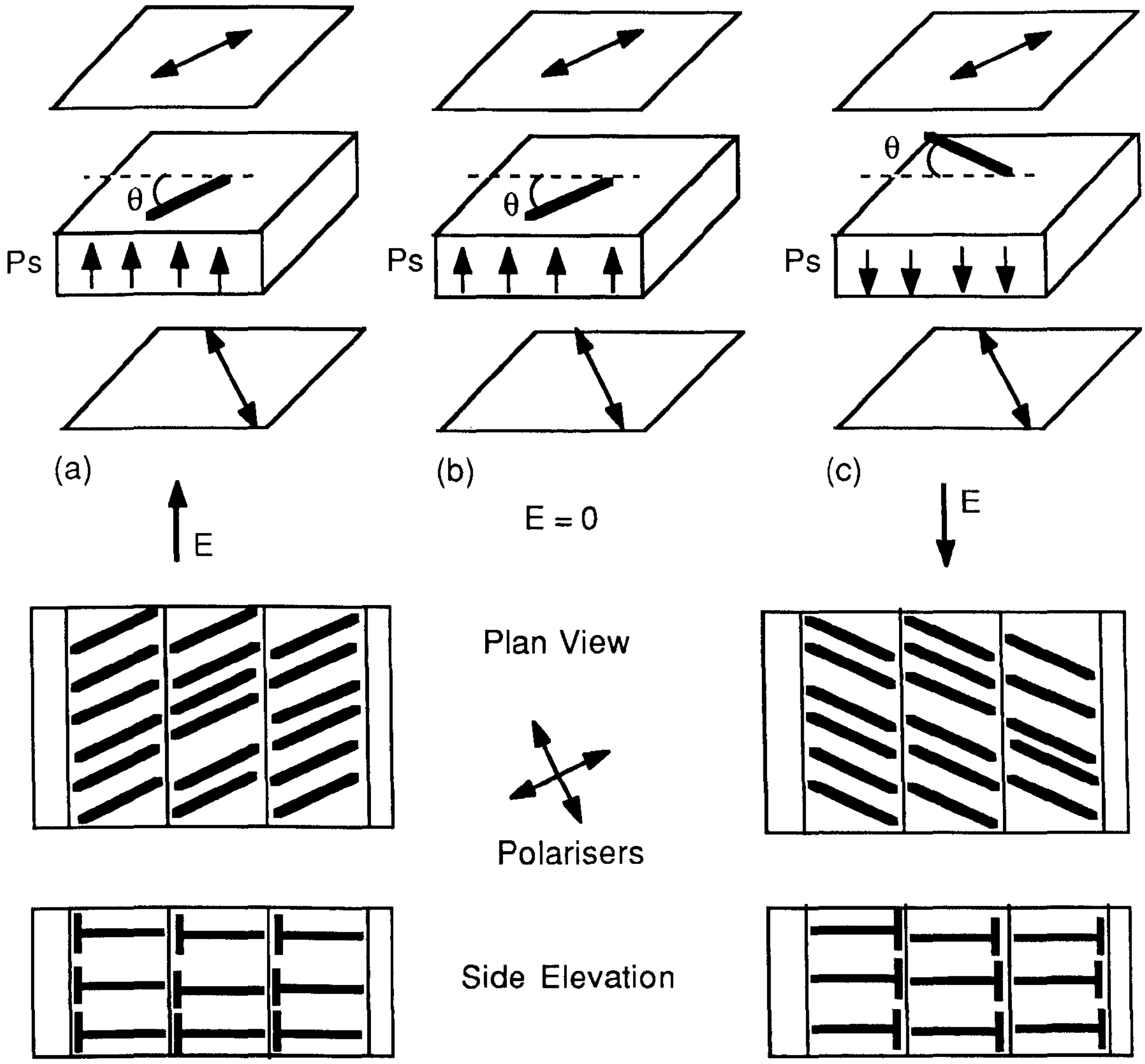
Hence, in the perfect situation the molecules can only be arranged as shown in Figure 23 (b) or (c) if the layers are not to be disrupted. It can also easily be seen how the molecules in Figure 23 (b) will move when switched to the orientational state shown in Figure 23 (c) [*i.e.* they will swivel about their axis through twice the tilt angle, ideally 45° (2 x 22.5°), with no interaction with each other].

Other chiral smectic mesophases can also be considered ferroelectric by the same argument.[97] The S_I* and S_F* phases are both more ordered and more viscous than the S_C* phase and therefore switching speeds between the two orientational states are much slower but the states are more stable.

Since the direction of the spontaneous polarisation (P_S) changes with the tilt direction through 360°, then in the bulk sample the P_S cancels out to zero; so whilst a chiral S_C layer is ferroelectric the bulk sample is not. In order to make use of the ferroelectric properties of the S_C* the helix has to be unwound. This has been done by several methods in the past *e.g.* by the application of an electric field normal to the helix and parallel to the smectic layers[98] and as the field increases the pitch length increases until it becomes unwound; or by using very thin cells (~2-3 μm) so that surface forces effectively unwind the helix and give the so-called surface-stabilized ferroelectric liquid device (Clark and Lagerwall[99]). However, the currently favoured method is to use chiral molecules of very long pitch length (~12 μm) in combination with very thin cells (*e.g.* ~2-3 μm; cell thicknesses of even 1.5 μm are now used, see p 44).

In the *quasi*-smectic disordered crystal mesophases which exhibit ferroelectricity (S_J*, S_G*, S_K*, S_H*) the formation of a helical structure is suppressed by the long-range inter-layer positional ordering of the constituent molecules.[100,101] However, only mono-domain samples of these crystal mesophases exhibit ferroelectric behaviour; multi-domain structures dominate and reduce ferroelectric properties. These very ordered crystal mesophases will be very viscous and have extremely slow switching speeds; however, they may show high levels of bistability which may provide a use as a storage medium.[101,102]

The cell construction for a ferroelectric (S_C*) display device is very similar to that for the twisted nematic display device (see p 25) in that it consists of a thin (1.5-3 μm) sandwich of liquid crystal (S_C*) material between two glass plates which have been specially treated (ITO electrode layer below a rubbed polyimide alignment layer). The mode of operation is shown in Figure 24 where the liquid crystal cell is placed between the two crossed-polarisers; in (a) the top polariser is in line with the long molecular axis of the constituent molecules (*i.e.* the direction of polarisation coincides with the optic axis, ideally tilted at 22.5° with respect to the layer normal) and the lower polariser is placed at 90° and therefore no light is transmitted (cell appears dark). When the field is removed nothing happens, and this illustrates the bistability of the device. If the field is reversed, then the P_S couples with the field and the molecular tilt direction changes through twice the tilt angle



The Operation of The Ferroelectric Display

Figure 24

(ideally 2 x 22.5°). The mode of switching in this device is interesting because in the twisted nematic device the molecules have to move through 90° about an axis at right angles to the molecular axis and in order to do so they encroach on the volume occupied by other molecules. The molecules in the ferroelectric device rotate on the surface of a cone through 45° and so they do not interfere with other molecules, the switching is much easier [see Figure 24 (a) and (c)]. The long molecular axis is rotated through 45° with respect to the polarisers and in effect the material becomes a half wave plate which rotates the plane of incident polarised light through 90° and allows light to be transmitted (cell appears bright). The lower section of Figure 24 illustrates the same principles and shows the two different orientational states in a plan view and side elevation; the alignment and layer arrangements can be seen in more detail.

Switching time (τ) can be represented according to Expression 10;

$$\tau \sim \frac{\gamma \sin \theta}{P_S E} \qquad (10)$$

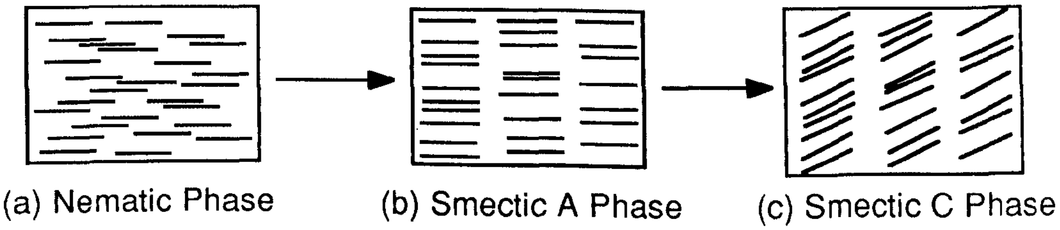
where γ is the viscosity of the ferroelectric material, θ is the tilt angle, P_S is the spontaneous polarisation and E is the electric field strength.[103]

The intensity of the transmitted light [Figure 24 (c)] strongly depends on the optical path difference (d x Δn), where d is the cell thickness[99,104] and is given by Equation 11.

$$I = I_0 \sin^2 (4\theta) \sin^2 \left(\frac{\pi d \Delta n}{\lambda} \right) \qquad (11)$$

I_0 is the intensity of light, of wavelength λ, passing through the cell in figure 24 (c) but with the analyser turned parallel to the polariser.

In order to obtain a fast switching time (τ), θ should be made as small as possible; however, this would have a disastrous effect on the contrast (since contrast is a maximum when $I = I_0$) and so θ is ideally kept at around 22.5 °. Increasing the field strength (E) would give a shorter switching time and as $E = V / d$ (where V is the voltage applied to the cell) this can be achieved by increasing the voltage or by decreasing the cell thickness. Finally, short switching times can be obtained by a high spontaneous polarisation or a low viscosity. However, a problem arises from high P_S in that current (A) flowing through the cell is induced by the switching process and is equal to the change in P_S per unit time. Therefore $A \propto P_S / \tau$ and from Expression 10, $A \propto P_S^2 / \gamma$. It is desirable to minimise A and since the current increases with the square of P_S then faster switching times are better obtained by aiming for low viscosity mixtures rather than mixtures of high P_S.


(a) Nematic Phase (b) Smectic A Phase (c) Smectic C Phase

The Ideal Phase Sequence for Alignment in the Ferroelectric Display

Figure 25

Of great importance to the success of this device is the alignment in the cell which is ideally achieved by having the cooling phase sequence of I-Ch*-S_A-S_C* for the mixture.[105] The supporting glass surfaces are treated with polyimide which is rubbed in a unidirectional manner with nylon, this gives good homogeneous alignment of the cholesteric phase [Figure 25 (a)]. The cooling of this well aligned state facilitates the formation of a well aligned layered S_A phase giving the so-called bookshelf alignment [Figure 25 (b)]. On further cooling it is the molecules within the layers that tilt to give the S_C* phase which is required for the ferroelectric display device [Figure 25 (c)].

The state of the art method of formulating S_C* mixtures is to first formulate a eutectic mixture of achiral compounds (host materials) and dope this with ~5-10% of a long pitch chiral compound (which does not necessarily exhibit an S_C* phase, but obviously must not depress the S_C* phase thermal stability too much) to give a chiral S_C mixture (see also p 48).

The ferroelectric display device (which was first demonstrated by Clark and Lagerwall[99] in 1980) has the advantage of sub-microsecond response times combined with a good viewing angle and bistability. This suggests potential for large area, complex displays with very high multiplexing capacity. The main advantage of the ferroelectric device is that due to the bistability it has high level multiplexability. In order to obtain an optical path difference (d x Δn) of 0.28 for maximum contrast with materials of $\Delta n = 0.19$, d needs to be 1.5 μm. Accordingly, most ferroelectric devices are now constructed with a cell spacing of 1.5 μm and are reported[106] to give good white-coloured clear written information which remains at least for many weeks and up to several months. However, one disadvantage of a 1.5 μm cell spacing is that some bistable states are separated by only 12-14° which gives a low contrast ratio (8:1) in comparison to a directly driven device but nevertheless their appearance is good. Multiplexing in the inverse mode (*i.e.* on the 'upturn' of the electrooptical characteristic) enables better discrimination between on and off data signals to be made, and this allows a broader range of multiplexing conditions to be used making the device easier to drive. Since the discrimination is improved it is also possible to reduce the 'data' voltage and hence reduce the optical noise it produces on the device giving a better appearance. The use of thin cells also has the advantage that the birefringence of the S_C* mixture need not be as low as with thicker cells. Ideally the optical path difference (Δn x d) should be 0.28 μm and since all reasonable S_C materials of high negative dielectric anisotropy at the present time have birefringence (Δn) values of 0.15-0.20 then a cell thickness of 1.5 to 2.0 μm is necessary. This requirement contrasts with the high optical path difference (Δn x d) needed for the ECB device (see p 35).

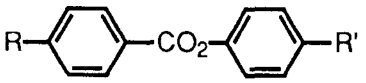
Introducing colour to ferroelectric display devices is a straightforward matter of using colour polyimide filters with best brightness results for devices with the indium oxide and tin oxide (ITO) electrodes deposited on top of the filters. Lack of grey scale is the main obstacle for a full colour ferroelectric display but it can be introduced using either of two possible techniques (time dither or spatial dither); time dither is presently favoured.

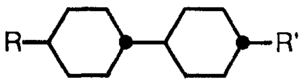
Several companies have manufactured demonstrator devices which look very promising but much work still has to be done in order to develop a display which can be mass produced. Difficulty arises from the need for thin cells made to very exact tolerance levels, especially if large panels are to be made to exploit the inherent high level multiplexability. Besides their use for fast-switching high-level multiplexed display devices, ferroelectric mixtures have potential use in fast switching light shutter devices for example in non-impact printers[107,108] which can replace laser printers.

1.7 (b) Liquid Crystal Material Requirements for Display Devices

1.7 (b) (i) Nematic Display Devices[109]

The success of nematic-based display devices is due entirely to the discovery of the cyanobiphenyls and their terphenyl analogues[11,12,110-112] by Gray *et al.* Early twisted nematic devices used eutectic mixtures of these compounds to achieve a nematic range of ~-10 to ~+60 °C with a positive dielectric anisotropy of ~11.0. Such mixtures were perfectly adequate when used solely for directly connected twisted nematic devices which are a 'forgiving' technology. However, when displays became slightly more complex (but still simple, *e.g.* watch and calculator displays) multiplex addressing was required (see p 29). This meant that nematic mixtures had to have their physical properties much more finely tuned to be used successfully, but a compromise is necessary, as improving one aspect is very often detrimental to another. For instance, $\Delta\varepsilon$ needs to be high to obtain a fast response time with minimal voltage and power comsumption, yet $\Delta\varepsilon / \varepsilon_\perp$ has to be low to give a sharp electrooptical characteristic which is essential for multiplex addressing. The disadvantage to the use of terminal cyano-substituted compounds as sole components of a twisted nematic mixture is that antiparallel correlation occurs which reduces $\Delta\varepsilon$ and gives high values of k_{33} / k_{11} whereas a minimal value of k_{33} / k_{11} is most important for a steep electrooptical characteristic.


(XV)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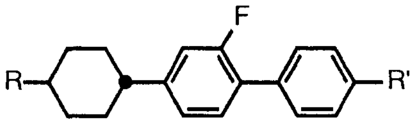
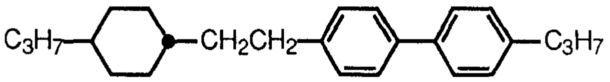
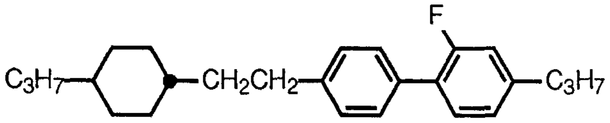
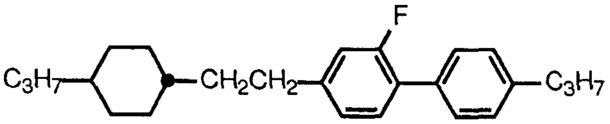

(XVII)


(XVIII)

K 67.0 S_A 119.0 N 144.0 I


(XIX)

K 40.0 N 108.0 I

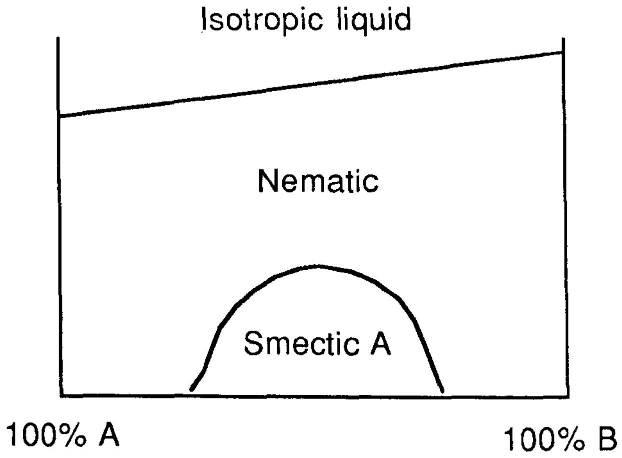

(XX)

K 59.0 (S_A 34.0) N 108.0 I

It is now universal practice[113] to use mixtures for multiplex-addressed twisted nematic devices which include both large and small positive $\Delta\varepsilon$ materials. An excellent practice is to use a host mixture of mainly non-polar ($\Delta\varepsilon$ = ~0) compounds (*e.g.* compounds XV-XX) which will give a low k_{33} / k_{11}, a low $\Delta\varepsilon / \varepsilon_\perp$ and a low viscosity; this mixture can then be doped with small amounts of a material with a very high positive

$\Delta\varepsilon$ which ensures that the mixtures have a good electrooptical characteristic combined with reasonably fast reponse times.

The problem arising from mixing large and small positive $\Delta\varepsilon$ materials is that, although none of the individual components may have a smectic phase, certain compositions of the mixture may have what is called an injected smectic phase (usually S_A) often persisting over wide temperature and composition ranges (see Figure 26). This smectic phase has an important influence on the nematic mixture and limits its lower operating temperature. However, an advantageous consequence is that as the smectic phase is approached, k_{33} / k_{11} decreases markedly[114-117] and this improves the multiplexability of displays. It is therefore desirable to formulate mixtures which are almost smectic but actually remain nematic at all temperatures (*i.e.* to choose a composition at the side of the smectic hump in Figure 26).[118]



Injection of Smectic Properties into a Mixture of Purely Nematic Compounds of High and Low Dielectric Anisotropy

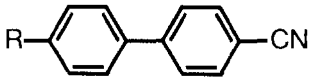
Figure 26

A lateral fluoro-substituent is often employed to subtly modify the properties of liquid crystal materials (see also p 14). Compound XVIII has a large smectic range and a smaller nematic range, but by using a lateral fluoro-substituent (compounds XIX and XX) the smectic tendency has been vastly reduced and the compounds have low melting points and wide nematic ranges. Also the lateral fluoro-substituent will simultaneously reduce $\Delta\varepsilon / \varepsilon_{\perp}$ (by increasing $\varepsilon_{\perp}$) and reduce k_{33} / k_{11} (by increasing the width to length ratio).

Mixtures used for the supertwisted birefringent effect device can be those used for the multiplex addressed twisted nematic device because only the display parameters have changed. The only alteration is the addition of the chiral dopant to induce the required degree of twist (see p 29).

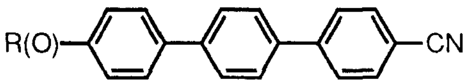
1.7 (b) (ii) Smectic A Display Devices[119]

The cyanobiphenyls and terphenyls used in the twisted nematic device are again the basis for mixtures used in the display devices utilising a smectic A mixture of positive dielectric anisotropy.

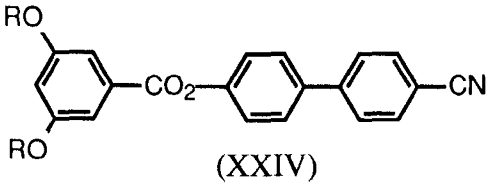


(XXI) $R = C_8H_{17}$

(XXII) $R = C_{10}H_{21}$



(XXIII)



(XXIV)

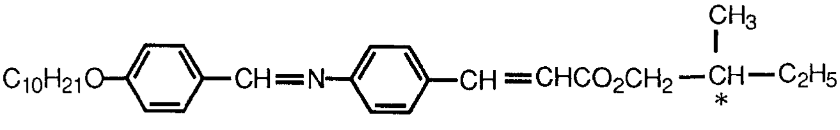
The higher homologues have moderate S_A ranges with small nematic ranges, a mixture of XXI and XXII has transition temperatures of K 5.0 S_A 40.0 N 43.0 I.[120] Mixtures with wide S_A ranges can be made by using compounds XXI, XXII and XXIII as a base mixture, compound XXIV being used to reduce the nematic range.[121]

1.7 (b) (iii) The Ferroelectric (Chiral Smectic C) Device[119]

This section is of particular relevance to the synthetic work reported in this thesis because of the emphasis on the preparation of host materials for the S_C* device and it should be read in conjunction with the results and conclusions section (p 298).

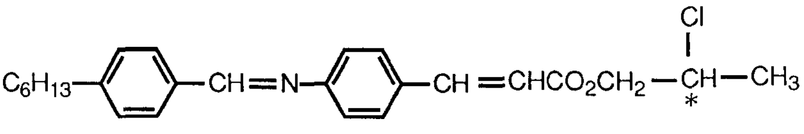
The first S_C* device was operated using compound XXV (DOBAMBC)[95] as the sole component but like most S_C*-exhibiting chiral compounds its P_S is very low.

Compound (XXVI)[122] was then used and has a much higher P_S[123] but a shorter S_C* range. Schiff's base type compounds (Mora compounds[124]) were prepared in an



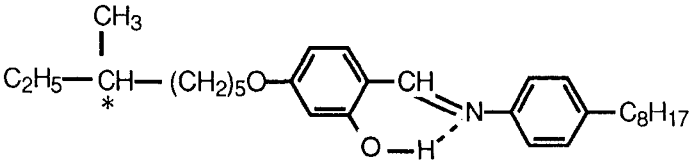
(XXV)

K 76.0 (S_I* 63.0) S_C* 95.0 S_A 117.0 I



(XXVI)

K 65.0 S_I* 74.5 S_C* 81.0 S_A 136.0 I



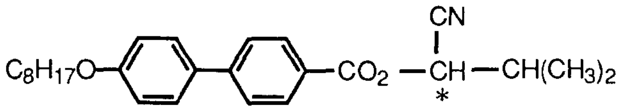
(XXVII)

K 12.0 S_C* 97.0 I

attempt to produce room temperature S_C* materials (*e.g.* compound XXVII) but these compounds have low P_S and tilt angles of only 8°. The conclusion drawn from this early work was that room temperature, wide S_C* range compounds of high P_S are very unlikely to be found. It was shown in 1980[125] that an achiral S_C phase doped with chiral molecules such as *L*-menthol gave a ferroelectric (S_C*) phase. Therefore ferroelectric mixtures are now formulated by preparing an achiral eutectic host mixture with all the desirable properties such as low melting point, wide S_C range (with short S_A and short nematic phase ranges above), negative Δε, low viscosity and very low optical path difference (Δn x d). A chiral dopant of very high P_S is chosen (which will probably not show an S_C phase due to the molecular structure required to give the high P_S) which will induce chirality into the mixture. Only 5-10% or less of this dopant is required and this should not significantly alter the desirable properties of the host mixture. Compound XXVIII is currently one of the best chiral dopants.[126]

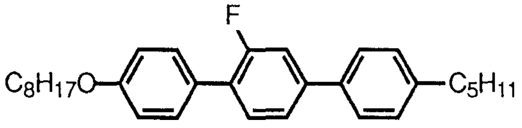
This method of formulating ferroelectric mixtures has become extremely successful because the physical property requirements are easier to obtain and can be changed easily by using different proportions or by introducing new compounds into the mixture.

Host materials used include compounds of types **301**[127-130] and XXIX[131] and the



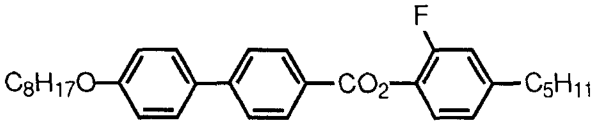
(XXVIII)

K 67.0 I



(301)

K 47.0 (S_J 40.0) S_I 53.5 S_C 116.5 S_A 130.0 N 155.0 I



(XXIX)

K 49.0 S_C 121.0 S_A 128.0 N 164.5 I

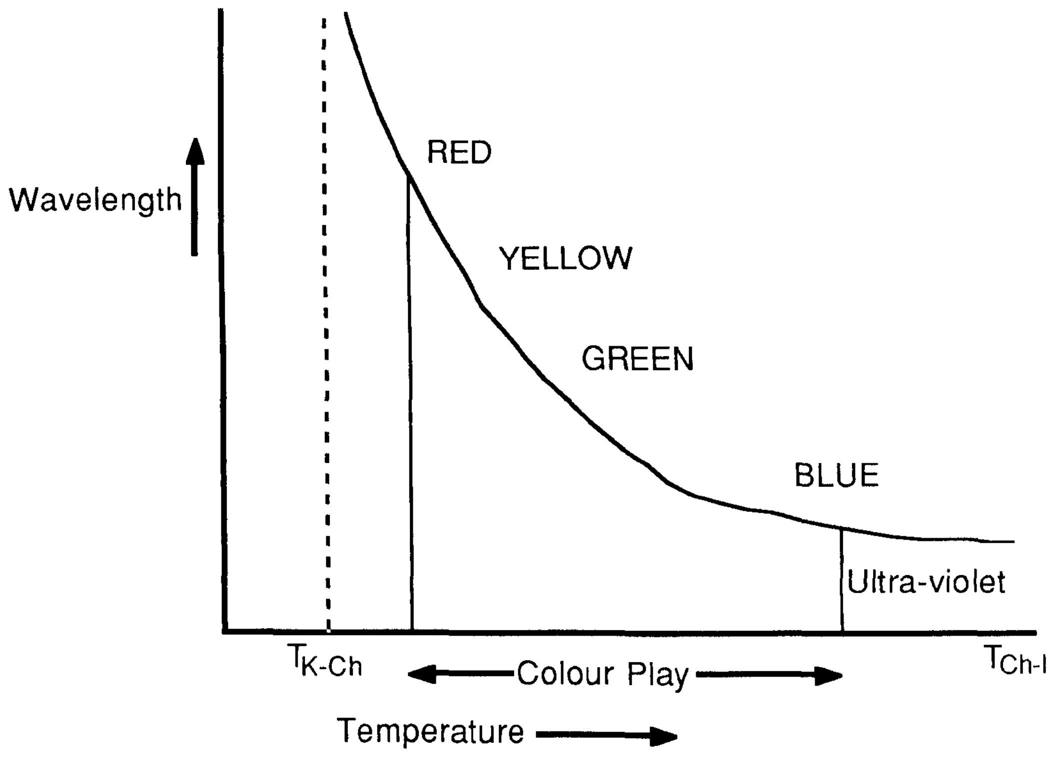
homologues chosen represent low melting compounds with large S_C ranges. Formulating mixtures of different homologues with an appropriate chiral dopant (*e.g.* compound XXVIII) enables room temperature S_C* mixtures to be obtained. The compounds of type XXIX (called MBF esters) have been most successful because they have Δε values of ~-1.5 and the absence of an underlying smectic phase. The monofluoroterphenyls (**301**) are adequate in producing S_C* mixtures and have a much lower viscosity than the MBF esters, but they are of slight positive Δε and underlying smectic phases can cause problems.

The field of ferroelectric liquid crystal display devices is attracting much attention at present and the results and conclusions of some novel ferroelectric host materials prepared in this work are discussed on p 298.

1.7 (c) Temperature Measurements and Surface Thermography[24]

This technology employs cholesteric liquid crystal materials. The structure of the cholesteric phase was discussed on p 6 and was shown to consist of a helical structure. The pitch length of the helix is temperature dependent and the helical structure causes selective reflection of light. Therefore, if the pitch length is of the order of the wavelength of visible light, then spectacular colour changes in the reflected light are seen on varying temperature. The wavelength of the reflected light decreases with increasing temperature so a blue colour indicates a higher temperature than a red colour (see Figure 27). This provides a means of monitoring changes in ambient or surface temperatures by observing the colour changes of cholesteric materials. Since the cholesteric temperature range is limited in single compounds, mixtures of compounds are used to give wide operating ranges.

In practice, the cholesteric material is made into an 'ink' by encapsulating[132] it in a polymer. Two encapsulation techniques are used; (i) gelatin microencapsulation[133] involves encasing droplets of cholesteric material in polymer shells, these shells are then added to a water/polymer solution to give a slurry; (ii) the polymer dispersion technique[134-136] is similar but the droplets of cholesteric material are directly dispersed into a polymer without a precoating process. These cholesteric inks are usually sandwiched between a transparent supporting substrate and a black absorbing layer and are seen in the form of a plastic sheet. The main use of these plastic sheets is for digital thermometers,



The Selective Reflection of Light Shown by Cholesteric Materials

Figure 27

and the temperature is indicated by a green selective reflection occurring beneath a fixed legend.

The colour change effect is sensitive enough to be used for medical applications[137] to detect skin disorders, subcutaneous tumors, breast cancer and blood clots by measuring slight temperature differences over the affected areas. Cholesteric inks are either painted on top of a black stain or are stretched in a black elastomeric film over the area of investigation. Either way, medical thermographic diagnosis is not totally reliable and has disadvantages when compared to the use of infra-red diagnostic techniques.

The technique is also important in engineering applications where components (*e.g.* turbine blades) can be coated with cholesteric materials (which are often required to withstand very high temperatures) to detect local heating. This enables engineers to develop better cooling systems for engines. Cholesteric mixtures also allow the non-destructive testing[138] of welds and electronic circuits and the investigation of turbulence and laminar airflow over surfaces. The use of cholesteric materials is a practical, low-cost way to detect radiation. The effect of impurities on the selective reflection wavelength has been investigated to show the potential use of cholesterogens in the detection of atmospheric pollution.

However, the largest market for cholesteric materials is for novelties. They are used to make commodities more attractive to purchasers (*e.g.* in cosmetics). Clothing, paints and wall-papers use cholesteric materials to reveal a colour change with changing temperature. Plastic sheets incorporating cholesteric mixtures make very accurate thermometers which are useful as well as having a novelty value.

1.7 (d) Structure Elucidation and Analysis

The use of a nematic liquid crystal as a solvent in nuclear magnetic resonance studies[139,140] of certain organic compounds can yield a much greater level of structural information than is conventionally possible. This is because the nematic solvent molecules tend to orientate the solute molecules to the extent that all of the dipole-dipole interactions are not reduced to zero as is normally the case with conventional isotropic solvents. Therefore, by use of computer processing, information of molecular ordering, chemical shifts and bond lengths and angles can be obtained.

The use of both nematic and smectic liquid crystals as stationary phases in gas-liquid chromatography[141] has achieved considerable success; particularly for the separation of geometrical isomers where conventional methods have failed. This is possible because the anisotropic nature of the liquid crystal material makes it particularly sensitive to small differences in the geometrical shapes of molecules and consequently this gives better resolution.

1.7 (e) Applications of Liquid Crystal Polymers[16,17,18]

The field of liquid crystal polymers is relatively new and is the subject of intense research at the present time. The field is beyond the scope of this thesis but some important applications need to be mentioned.

Liquid crystal main chain polymers[16,17] (mesogenic units form part of the polymer backbone), in general, show nematic phases at certain compositions in suitable solvents (lyotropic nematic). However, obtaining a thermotropic nematic mesophase can lead to problems.[16]

The most important property of liquid crystal main chain polymers in the nematic phase is the ease of homogeneous orientation of shear. This macroscopic orientation gives rise to a lower viscosity than the isotropic liquid phase (despite the lower temperature). Therefore the extrusion or fibre spinning of such polymers in the nematic phase is technologically important as processing temperatures can be reduced and mould filling facilitated. The macroscopic orientation which exists on processing remains in the solidified material and confers outstanding mechanical properties such as high tensile strength, high flexural strength and improves flexural moduli and impact strength. The absence of shrinking and low coefficients of thermal expansion are other features which make liquid crystal main chain polymers attractive for use as fibres, extrudates and reinforced resins. Kevlar[16,17,142] is the most well known liquid crystal main chain polymer and forms a nematic phase in sulphuric acid. Kevlar was developed by Du Pont and is a light and very strong material which has found many uses including uses in the manufacture of motor vehicles, aircraft and in bullet-proof vests.

The ever increasing demand for light-weight, very strong materials to replace conventional materials means an exciting future is in prospect for main chain liquid crystal polymers.

Liquid crystal side chain polymers[16,17,18] (mesogenic units are attached as side chains from the polymer backbone) may exhibit nematic or smectic mesophases which depend solely on the structure of the side chain and they exhibit the same optical properties as conventional low molar mass liquid crystal materials. Liquid crystal side chain polymers, in contrast to their main chain analogues, do not possess any particular outstanding mechanical properties. Side chain liquid crystal polymers form a glass as the liquid crystalline melt is cooled and this results in the molecular orientation of the liquid crystalline state being retained in the glassy state. In the liquid crystal phase the molecular director can be changed by an electric or magnetic field in the same way as for low molar mass materials and on cooling this orientation is frozen in.[143]

The combination of these characteristics (the glassy state and the anisotropic physical characteristics) indicates potential applications in linear and non-linear optics[144] and in optical storage devices.[145]

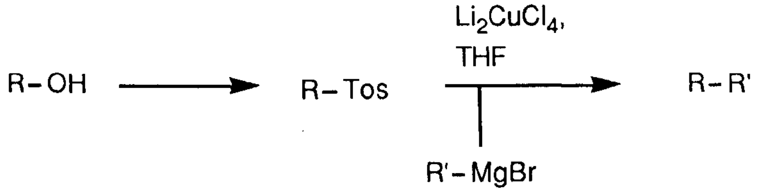
1.8 Carbon-Carbon Bond-forming Cross-coupling Methods

Perhaps one of the most desirable synthetic processes in organic chemistry is the formation of a carbon-carbon bond. Such a process is extremely useful because large molecules can be prepared *via* small, more easily managed units which are subsequently coupled together to give the desired product. The long, lath-like molecular structure of most liquid crystalline compounds makes cross-coupling reactions very important in such a fast-moving area of synthetic organic chemistry where display device engineers are demanding more advanced materials. Complications, however, can arise from homocoupled products which are often difficult to separate from the desired cross-coupled product and selectivity is usually required where two reactive sites exist, to enable a second cross-coupling reaction to be carried out and so facilitate the efficient synthesis of multi-unit compounds (*e.g.* *p*-terphenyls).

Since Corriu[146] and Kumada[147] reported in 1972 that cross-coupling of Grignard reagents with aryl and alkenyl halides could be catalysed by nickel-phosphine complexes, a wide variety of coupling reactions has been developed and some are of great synthetic importance. The synthetic utility of a variety of cross-coupling reactions has been demonstrated by work which shows that organometallics containing zinc,[148-151] aluminium,[152,153] zirconium,[154,155] tin,[156-158] and boron[159-164] can undergo cross-coupling reactions using a palladium catalyst.

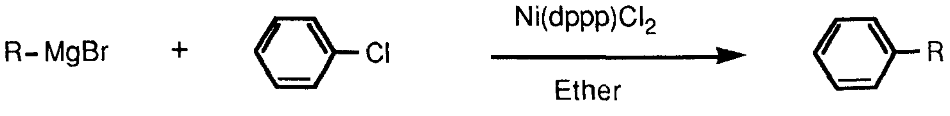
The following account represents a short review of carbon-carbon bond formation methods which the author has considered during work on the synthesis of liquid crystalline compounds.

Fouquet and Schlosser[165] (1974) reported the coupling of primary tosylates with a variety of Grignard reagents (*e.g.* alkyl, aryl).



The principal reason given for the occurrence of reaction is the chelation of the tosylate with the copper catalyst after the latter's interaction with the Grignard reagent. They also reported that a carbon-carbon bond can be formed by the replacement of allylic and benzylic acetate groups with Grignard reagents, presumably because a similar chelate complex can be formed. The author has attempted this procedure several times without any success (see attempted preparation of compound **32**, Method A) despite the excellent yields reported and the success of this method in some other systems.[166]

A more general cross-coupling method involving the nickel-phosphine complex-catalysed coupling of alkyl, aryl and alkenyl Grignard reagents with aryl and alkenyl halides was reported by Kumada *et al.*[167] (1976) and several nickel-phosphine complex catalysts were reviewed.



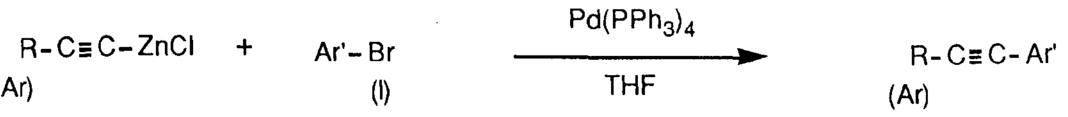
Generally the best catalyst is found to be nickel *bis*(diphenylphosphine)propane dichloride [$Ni(dppp)Cl_2$] and it is reported that fluorides, chlorides, bromides and iodides all undergo replacement. With this particular catalyst, the order of reactivity is unusual [PhI>PhCl>PhBr>PhF]; however, with this catalyst where there is competition for replacement and with nickel *bis*(diphenylphosphine)ethane [$Ni(dppe)Cl_2$] in all cases, the usual order of reactivity [PhI>PhBr>PhCl>PhF] is observed. However, dehalogenation occurs during the coupling process in the order PhF<PhCl<<PhBr<PhI and when THF is used as the solvent the rate of dehalogenation is much greater than when diethyl ether is used. Therefore, the coupling reactions are best catalysed by $Ni(dppp)Cl_2$ and carried out on aryl chlorides in diethyl ether to give the best compromise of low dehalogenation and high reaction yields. Despite the quantitative yields quoted, several attempts at this type of coupling have proved to be complete failures (see the attempted preparation of compound **32**, method B) although Chan[127] used the reaction with some success.

It was reported by Negishi, King and Okukado[148] (1977) that aryl bromides or iodides can be cross-coupled with aryl- or benzyl- zinc chlorides in the presence of 5 mol% of $Ni(PPh_3)_4$ or $Pd(PPh_3)_4$ [prepared from $Pd(PPh_3)_2Cl_2$ and 2 equiv. of di-isobutylaluminium hydride (DIBAL) and triphenylphosphine].

$$\text{Ar-ZnCl} \quad + \quad \text{Ar'-Br} \quad \xrightarrow[\text{THF}]{\text{Pd(PPh}_3)_4} \quad \text{Ar-Ar'}$$

The arylzinc chloride is readily prepared by the reaction of the corresponding aryllithium with zinc chloride and good yields of the desired cross-coupled product (with less than 5% homo-coupled product) are reported.

In 1978 Negishi and King[150] reported the very useful palladium tetrakis(triphenylphosphine)palladium(0) [$Pd(PPh_3)_4$] catalysed cross-coupling of alkynylzinc chlorides with aryl iodides and activated (*i.e.* by electron-withdrawing substituents, *e.g.* cyano) aryl bromides at room temperature in good yields. Recent work by the author (reported in this thesis) has shown that non-activated and even deactivated aryl bromides can undergo cross-coupling at elevated temperatures (~67 °C).



$$\underset{\text{(Ar)}}{\text{R-C}\equiv\text{C-ZnCl}} \quad + \quad \underset{\text{(I)}}{\text{Ar'-Br}} \quad \xrightarrow[\text{THF}]{\text{Pd(PPh}_3)_4} \quad \underset{\text{(Ar)}}{\text{R-C}\equiv\text{C-Ar'}}$$

This has led to a highly successful method of selective cross-coupling to 1-bromo-4-iodobenzene by use of an initial cross-coupling to the iodo-substituent at room temperature followed by another cross-coupling at elevated temperature. It has also been found by Chen and He[168] (1987) and by the author (1988) that phenolic triflate derivatives (see Experimental Discussion, p 234) couple to alkynylzinc reagents under similar conditions to aryl bromides. This cross-coupling reaction of triflates is important because it enables a carbon-carbon bond to be formed at a phenolic site (or from vinyl triflates obtained from carbonyl compounds) which is useful where halogen-containing starting materials are unavailable (*e.g.* in natural product chemistry; see also the synthesis of the naphthalene derivatives discussed in this thesis, p 234).

The method developed by Negishi and King is similar in its end result to the earlier cross-coupling method of Sonogashira *et al.*[169] (1975) which involves a direct coupling process of a terminal alkyne to an aryl iodide or an aryl bromide catalysed by either $Pd(PPh_3)_4$ or $Pd(PPh_3)_2Cl_2$ and copper(I) iodide. The latter procedure appears to be better than the equivalent zinc coupling method in that there is no need to make the alkynylzinc chloride, but the crude products are usually much more difficult to purify than those from the zinc coupling procedure.

The most recent and by far the best overall method of preparing unsymmetrical biaryl or multi-aryl systems was developed by Suzuki *et al.*[161] (1981) and later this method provided excellent results for Miller and Dugar[162] (1984) and the author[163,164] (1986).

$$\text{Ar-B(OH)}_2 \quad + \quad \underset{\text{(I)}}{\text{Ar'-Br}} \quad \xrightarrow[\text{Pd(PPh}_3)_4]{\text{Benzene, ethanol, 2M-Na}_2\text{CO}_3} \quad \text{Ar-Ar'}$$

This procedure involves the cross-coupling of an arylboronic acid with an aryl bromide or aryl iodide. The boronic acid can be easily prepared in excellent yield from an aryllithium or an aryl Grignard reagent by treatment with tri-isopropyl borate in dry THF at -78 °C under dry nitrogen (trimethyl borate gives lower yields), followed by the hydrolysis of the borate ester (*in situ*) with 10% hydrochloric acid.[170] The arylboronic acids are stable in air and are not sensitive to moisture; they can be prepared in large quantities, stored and used when required. The spectra of the 'boronic acids' frequently gives no confirmation of a boronic acid structure and the product often appears to be a mixture of anhydrides and boronic acid; the nature of the products is further complicated by their tendency to coordinate with THF, which accounts for their soft waxy nature and their poorly resolved nmr spectra. Addition of aqueous 10% potassium hydroxide to the product, removal of any impurity by an ether wash (*e.g.* any material produced by moisture reacting with the intermediate lithium or Grignard reagent or coordinated THF), followed by acidification and extraction into ether gives a crystalline solid with a well resolved nmr spectrum (although the -OH protons are still often not revealed); any anhydride originally present is converted into the boronic acid by this treatment. The coupling reaction is carried out in a two-phase medium of benzene or toluene and aqueous 2M sodium carbonate. The boronic acid is added in 10-20% excess and the reaction is catalysed by 3 mol% of tetrakis(triphenylphosphine)palladium(0) [$Pd(PPh_3)_4$]. The reaction is carried out under nitrogen to protect the catalyst and the stirred mixture is heated under reflux until glc analysis reveals a complete reaction (usually ~3-4 hours, but often overnight for convenience).

It has recently been found by the author that aryl triflates can be coupled with arylboronic acids in the same manner as aryl iodides and aryl bromides (see also Experimental Discussion, p 225 and 230). Aryl iodides react much faster than aryl bromides which are similar in reactivity to phenolic triflates; those compounds with electron-withdrawing groups (*e.g.* cyano-substituents) tend to react faster than others and overall yields are always high. By using iodo, bromo and triflate functional groups, selective coupling can be achieved which enables a subsequent coupling to be carried out (see Experimental Discussion, p 225, 230 and 235).

The boronic acid coupling reaction offers the advantages of high yields, clean products with no homocoupling, no necessity for anhydrous conditions and the boronic acid can be pre-prepared, stored and used when convenient.

A useful palladium-catalysed cross-coupling reaction which the author has not carried out is the vinylation of organic halides[171] (commonly referred to as the 'Heck

Reaction'). This is a convenient method for forming carbon-carbon bonds at unsubstituted vinylic positions as shown in the equation below.

The organic halide employed is restricted to aryl, heterocyclic, benzylic or vinylic types with a bromo- or an iodo- substituent (although it seems reasonable that aryl or vinyl triflates as used in other coupling processes would also couple).

Much work on the palladium-catalysed cross-coupling of organo-tin reagents with vinyl and aryl triflates has recently been reported by Stille.[157,158] This type of cross-coupling appears to be very versatile as alkyl, vinyl, alkynyl and aryl tin reagents are all reported to couple in the presence of lithium chloride (3 equiv.) and 2 mol% $Pd(PPh_3)_4$ or $Pd(PPh_3)_2Cl_2$ in high yields under mild conditions. Both catalysts are reported to give good results; although shorter reaction times and/or milder conditions apply to the latter, the former enabled selectivity to be achieved where two different reactive sites existed. The presence of lithium chloride is essential to the formation of the arylpalladium chloride (see Mechanism Suggestions, p 62) and this applies to all other cross-coupling procedures involving triflates.

On surveying the available literature it appears that although organometallic reagents of methyl, aryl, alkenyl, benzyl or alkynyl moieties have been successfully used for cross-coupling, those involving alkyl groups containing β-hydrogen atom(s) have not always given satisfactory results due to β-elimination. The cross-coupling of secondary or tertiary alkyl reagents has been found to be especially difficult because it is accompanied by isomerization of the alkyl group and/or the reduction of the halides.

Hayashi *et al.*[172] (1984) reported the development of a catalyst capable of facilitating the cross-coupling of secondary and primary alkyl Grignard reagents and alkylzinc reagents with aryl or alkenyl halides.

$$\underset{(ZnCl)}{R\text{-}MgBr} + Ar\text{-}Br \xrightarrow[THF]{Pd(dppf)Cl_2} R\text{-}Ar$$

The catalyst for this process is

dichloro[1,1'-*bis*(diphenylphosphino)ferrocene]palladium(II) [$Pd(dppf)Cl_2$] and is reported to produce the desired cross-coupled product in exceedingly high yield. The catalyst is thought to perform the reductive elimination process (see mechanism) much faster than β-elimination because of a large P-Pd-P angle and a small Cl-Pd-Cl angle.

More recently Castle and Widdowson[173] have reported the cross-coupling of alkyl Grignard reagents with alkyl iodides.

$$\text{R-MgBr} \quad + \quad \text{R'-I} \quad \xrightarrow[\text{THF}]{\text{Pd(dppf)Cl}_2,\ \text{DIBAL}} \quad \text{R-R'}$$

Good yields are made possible by pre-reducing the $Pd(dppf)Cl_2$ catalyst using di-isobutylaluminium hydride (DIBAL) which enables a faster oxidative addition process (see mechanism) (normally very slow for alkyl halides) and good yields are reported.

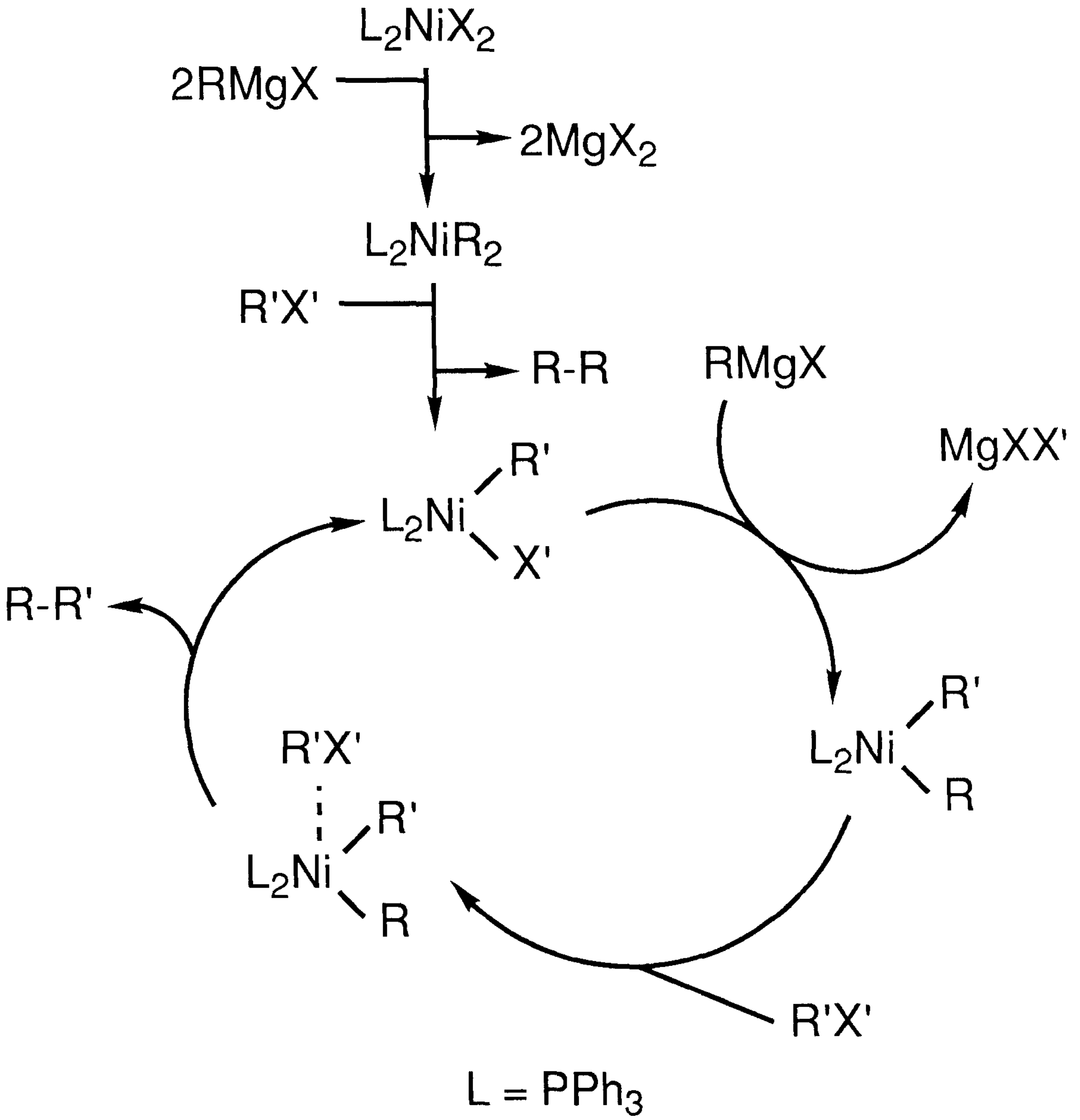
Mechanism Suggestions

Mechanisms for metal-catalysed cross-coupling reactions are not yet fully understood and few detailed proposals are available in the literature with even fewer experimentally proven mechanisms.

The mechanism suggested by Kumada *et al.*[167] (1976) for the nickel-phosphine complex-catalysed Grignard coupling is given in Figure 28.

This mechanism (Figure 28) shows a pre-cycle step which produces 1mol of homo-coupled product (from the metal derivative) for every mol of catalyst and therefore, cannot be applied to the coupling procedures involving arylboronic acids or alkynylzinc reagents because absolutely no such homo-coupled product has ever been identified (or even suspected).

A mechanism (Figure 29) presented by Scott and Stille[157] (1986) is based on experimental evidence of intermediates involved in the procedure and is consistent with a lack of homo-coupled products but it is quite similar in some respects to the mechanism suggested by Kumada *et al.*[167] (1976). Although this mechanism is based on findings for the vinyl triflate coupling with organo-tin reagents, it is easily adapted to account for others (*e.g.* arylboronic acid and alkynylzinc coupling reactions to aryl halides or aryl triflates).



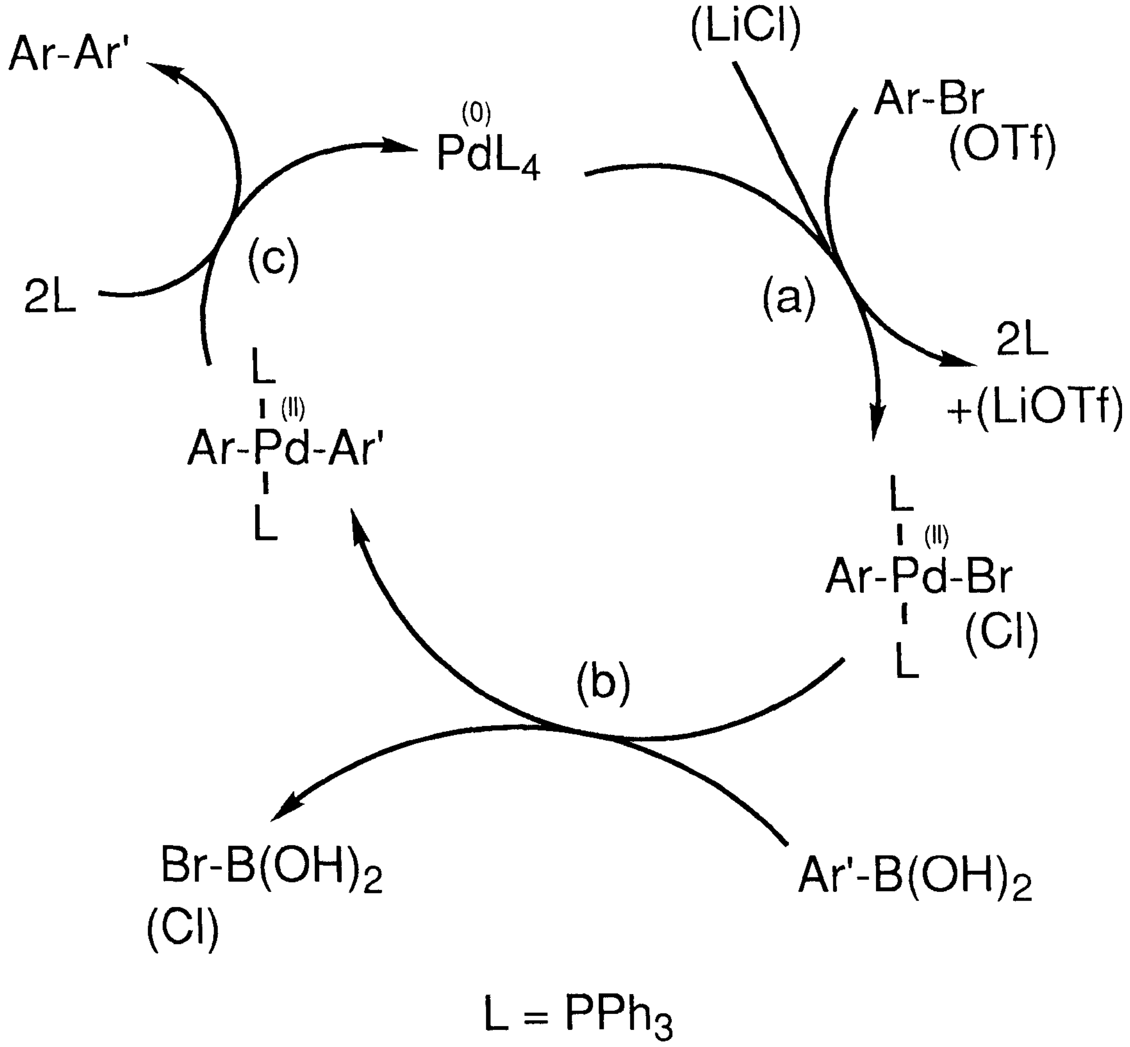
A Proposed Mechanism for the Cross-coupling of Grignard Reagents with Aryl and Alkenyl Halides

Figure 28

The mechanism shown in Figure 29 illustrates the much used arylboronic acid coupling with an aryl bromide and the aryl triflate example is shown in brackets to illustrate the essential role of the lithium chloride.

As a further illustration, Figure 30 shows the possible movement of electrons in the steps of the mechanism which form the product.

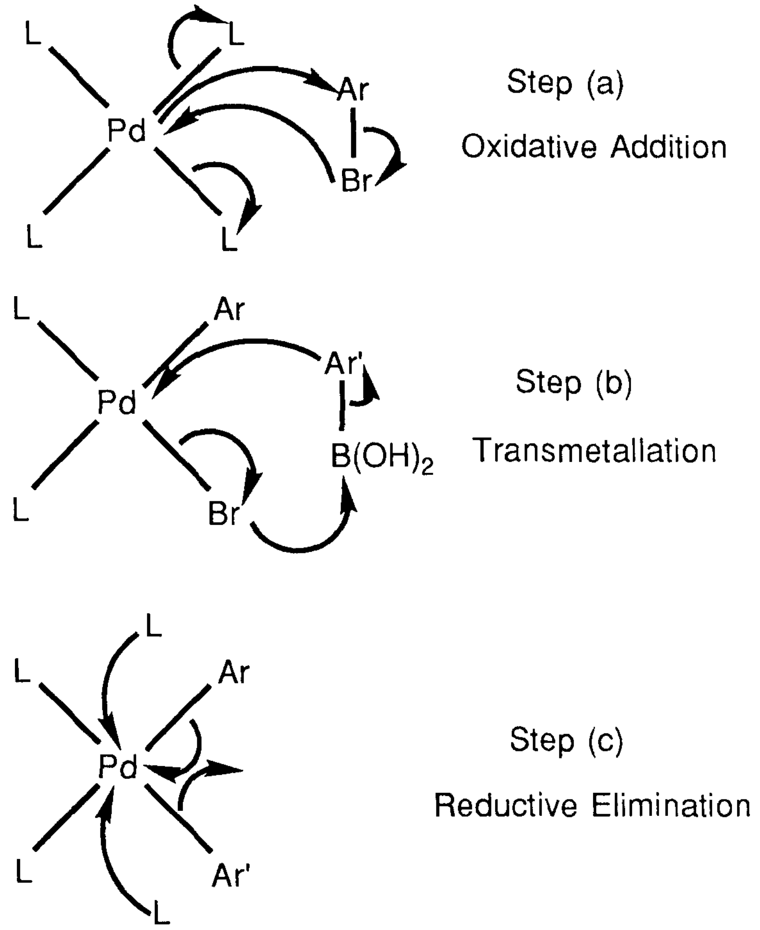
Step (a) shows the oxidative addition of the aryl bromide with the loss of two triphenylphosphine ligands to give the palladium(II) species. Step (b) is a simple transmetallation step and step (c) is the reductive elimination which regenerates the catalyst and yields the desired cross-coupled product.



A Proposed Mechanism for the Cross-coupling of Arylboronic Acids

with Aryl Halides or Aryl Triflates

Figure 29



L = PPh_3

Detailed Steps for the Mechanism in Figure 29

Figure 30

In summary, the use of cross-coupling reactions such as those outlined in this section is essential for the viable future synthesis of liquid crystals. By the use of selective cross-coupling procedures, complex moieties can be synthesised and then coupled together in a high-yielding final step. The possible use of particular units for several different synthetic processes permits a fast, economic and systematic method of synthesis.

EXPERIMENTAL

2.1 Aims

The broad aim of the work was to synthesise novel liquid crystal materials of specific structure to enable their use in contemporary technological devices (mainly display devices).

More specifically, the work can be divided into three main areas of the liquid crystal field: (i) the esters with a terminal cyano-substituent (Schemes 1-9) were intended to be nematic materials of very high positive dielectric anisotropy ($\Delta\varepsilon$) values for potential use as additives in nematic mixtures for display devices; (ii) the biphenyls and terphenyls with lateral fluoro-, cyano- or trifluoromethyl- substituents (Schemes 10-32) were expected to give smectic C materials of negative dielectric anisotropy which would make excellent host materials in the ferroelectric (chiral smectic C) display device; (iii) the materials incorporating a 2,6-disubstituted naphthalene moiety (Schemes 33-37) were intended to be nematic materials (ideally with low melting points) which show a high optical anisotropy (Δn) and a high polarisability. Such compounds have a potential use in a new technology non-display device.

The aims are discussed in more detail in the appropriate Results and Conclusions sections.

2.2 Assessment of Materials

2.2 (a) Determination of Transition Temperatures

2.2 (a) (i) Optical Microscopy

The transition temperatures of all mesogens were determined using an Olympus BH2 polarising microscope in conjunction with a Mettler FP52 heating stage and FP5 control unit. This allows fast or slow heating and cooling of samples over the range -20 to 300 °C with an accuracy of ±0.2 °C. Cooling from just above room temperature down to -20 °C is achieved by passing a precooled (in liquid nitrogen) stream of nitrogen through the stage and over the sample.

2.2 (a) (ii) Differential Scanning Calorimetry (DSC)

All mesogens were subjected to thermal analysis by using a Perkin-Elmer DSC-2C differential scanning calorimeter with a data station (see also Identification of Mesophase Type, p 22). In some cases samples were heated and then cooled at an initial rate of 20 °C per minute to enable the sample to settle in the DSC pan and then repeated at 10 °C per minute. However, this is not necessary for low relative molecular mass materials and often has a detrimental effect in melting a sample which will not readily crystallise or will crystallise to a different crystal form. This may make the 10 °C per minute cycle unrepresentative of the material. One cycle carried out at 10 °C per minute gave well defined, sharp peaks with accurate transition temperatures and is much less time consuming than performing two runs per sample.

The cooling in most cases was provided by using liquid nitrogen, however, in some cases a Perkin-Elmer intracooler provided the refrigeration. A static nitrogen atmosphere was used in the furnace and the reference material was aluminium oxide (Al_2O_3). Indium metal was used as the standard for callibration purposes.

2.2 (a) (iii) Virtual Transition Temperatures

When a 'final' compound intended for use in a liquid crystal environment did not exhibit any enantiotropic or monotropic mesophases then a virtual or extrapolated T_{N-I} value was determined. This was achieved by preparing a series of binary mixtures, of known composition, of the test compound with a standard nematogenic mixture of known T_{N-I} value. The standard used was supplied by our collaborators (BDH Chemicals Limited) and is called E7. This commercial mixture contains 4-cyano-4'-*n*-alkylbiphenyls and 4-cyano-4'-pentyl-1,1':4',1''-terphenyl and has a T_{N-I} value of 60.0 °C. By extrapolating the straight line produced to the 100% test compound composition the T_{N-I} value is determined and is conventionally given in square brackets [].

2.2 (b) Chromatography Techniques

2.2 (b) (i) Analytical Thin-Layer Chromatography (tlc)

The tlc plates used were aluminium sheets coated with silica gel 60 F254 (Merck).

2.2 (b) (ii) Column Chromatography

Column chromatography was carried out using standard grade silica gel (Fisons, 60-120 mesh) or flash chromatography[174] grade silica gel (Merck 9385) unless otherwise stated.

2.2 (b) (iii) Gas-Liquid Chromatography (glc)

The progress of many reactions was followed by using a Perkin-Elmer 8320 capillary gas chromatograph equipped with a BP1 capillary column.

2.2 (b) (iv) High Performance Liquid Chromatography (hplc)

The hplc system used to check the purity of all 'final' compounds consisted of the following modules: (i) a Kontron 420 Pump; (ii) a Must Multi-port Stream Switch; (iii) a Perkin-Elmer ISS-100 Auto Sampler; (iv) a Dynamax Microsorb C18 Reverse Phase Column; (v) a Spectroflow 757 Absorbance Detector; (vi) a Chessell Chart Recorder; (vii) a Perkin-Elmer Data Station.

2.2 (c) Spectroscopy

2.2 (c) (i) Nuclear Magnetic Resonance Spectroscopy (nmr)

A Jeol JNM-GX270 nmr spectrometer (270 MHz) was used to obtain high resolution ^1H nmr spectra for every compound which was prepared.

2.2 (c) (ii) Infra-Red Spectroscopy (ir)

Infra-red spectroscopy was carried out using a Perkin-Elmer 783 infra-red spectrophotometer.

2.2 (c) (iii) Mass Spectrometry (ms)

A Finnigan-MAT 1020 gc/ms spectrometer was used to record mass ion data.

2.2 (d) Purity of Compounds Synthesised

All the compounds prepared were subjected to high resolution (270 MHz) ^1H nmr spectroscopy and a perfect ^1H nmr spectrum was one consideration of purity.

All compounds prepared were subjected to glc analysis (where possible) and/or tlc analysis and satisfactory results were obtained.

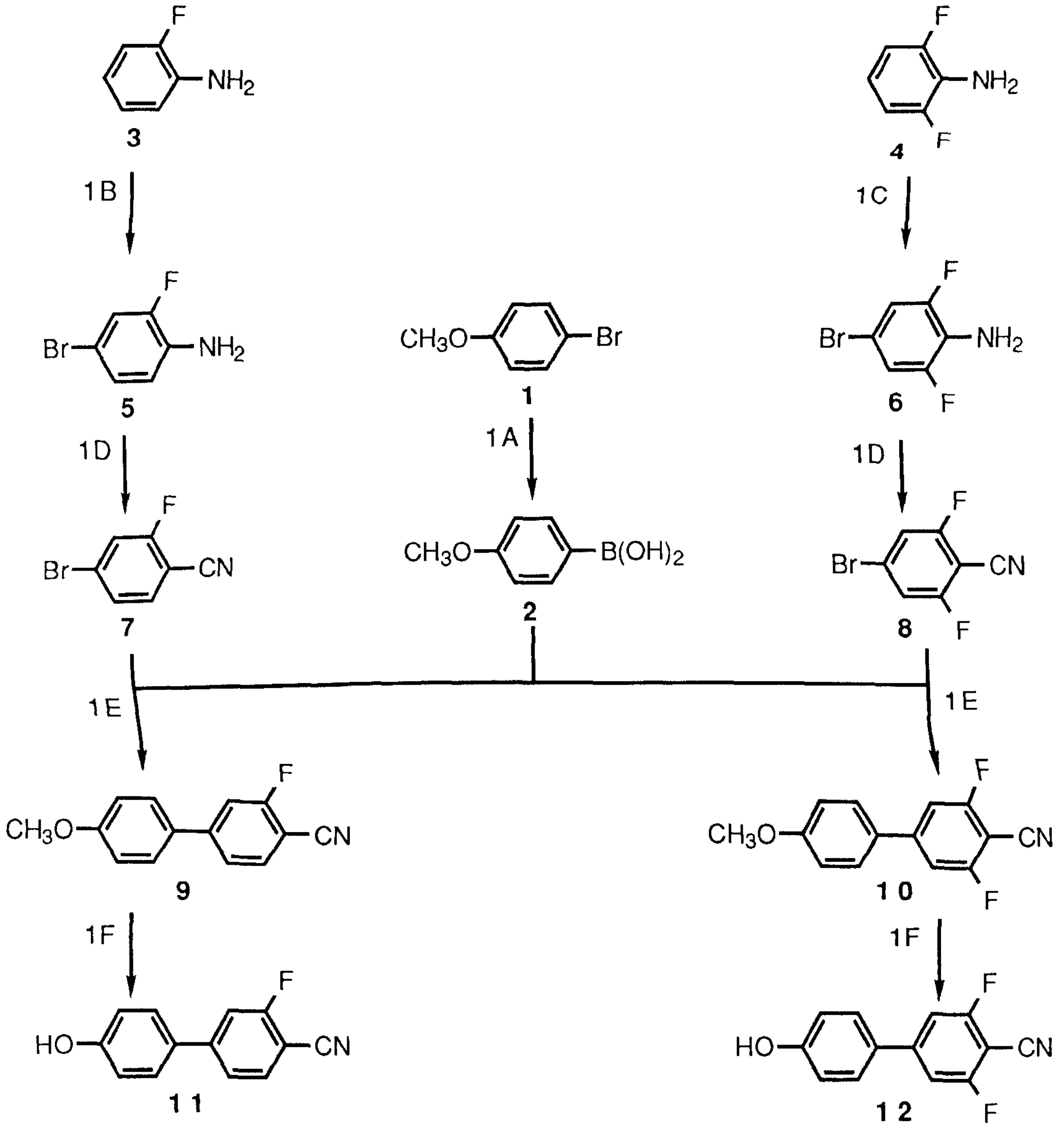
The purity of all the 'final' compounds was checked by hplc analysis and they were found to be greater than 99.5% pure except were stated otherwise.

2.3 Abbreviations and Nomenclature

Abbreviations used and their meaning are as follows: mp = melting point; bp = boiling point; K = crystalline solid phase; I = isotropic liquid phase; N = nematic liquid crystal mesophase; Ch = cholesteric liquid crystal mesophase; S = smectic liquid crystal mesophase (with subscript letters A, B, C, F and I) or *quasi*-smectic crystal mesophase (with subscript letters E, G, H, J, K and L); * = chirality in a phase (*e.g.* chiral smectic C is denoted by S_C*); THF = tetrahydrofuran; DMF = dimethyl formamide.

Generally the IUPAC system of nomenclature has been followed but in some cases deviations have been allowed in the interest of clarity. All terphenyls prepared are of the 1,1':4',1" type (*i.e.* *p*-terphenyls) and this prefix has therefore been omitted from the compound names in the text.

Scheme 1 (p 107-111)



1A ...... (i) Mg, THF; (ii) (^{i}PrO)$_3$B, THF; (iii) 10% HCl.

1B ...... NBS, CH_2Cl_2.

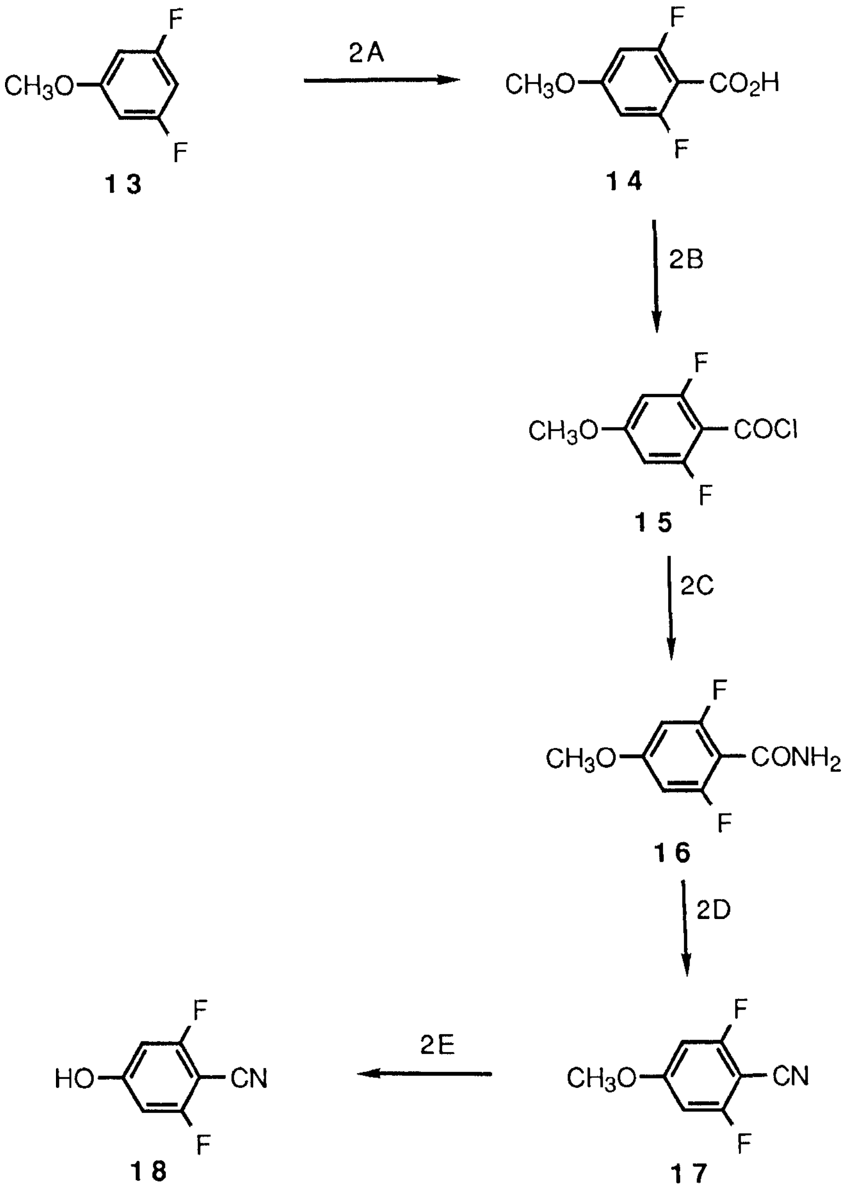
1C ...... Br_2, HOAc.

1D ...... (i) $NaNO_2$, H_2SO_4; (ii) $CuSO_4.5H_2O$, KCN.

1E ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

1F ...... BBr_3, CH_2Cl_2.

Scheme 2 (p 111-113)



2A ...... (i) nBuLi, THF; (ii) CO_2 (solid), Et_2O.

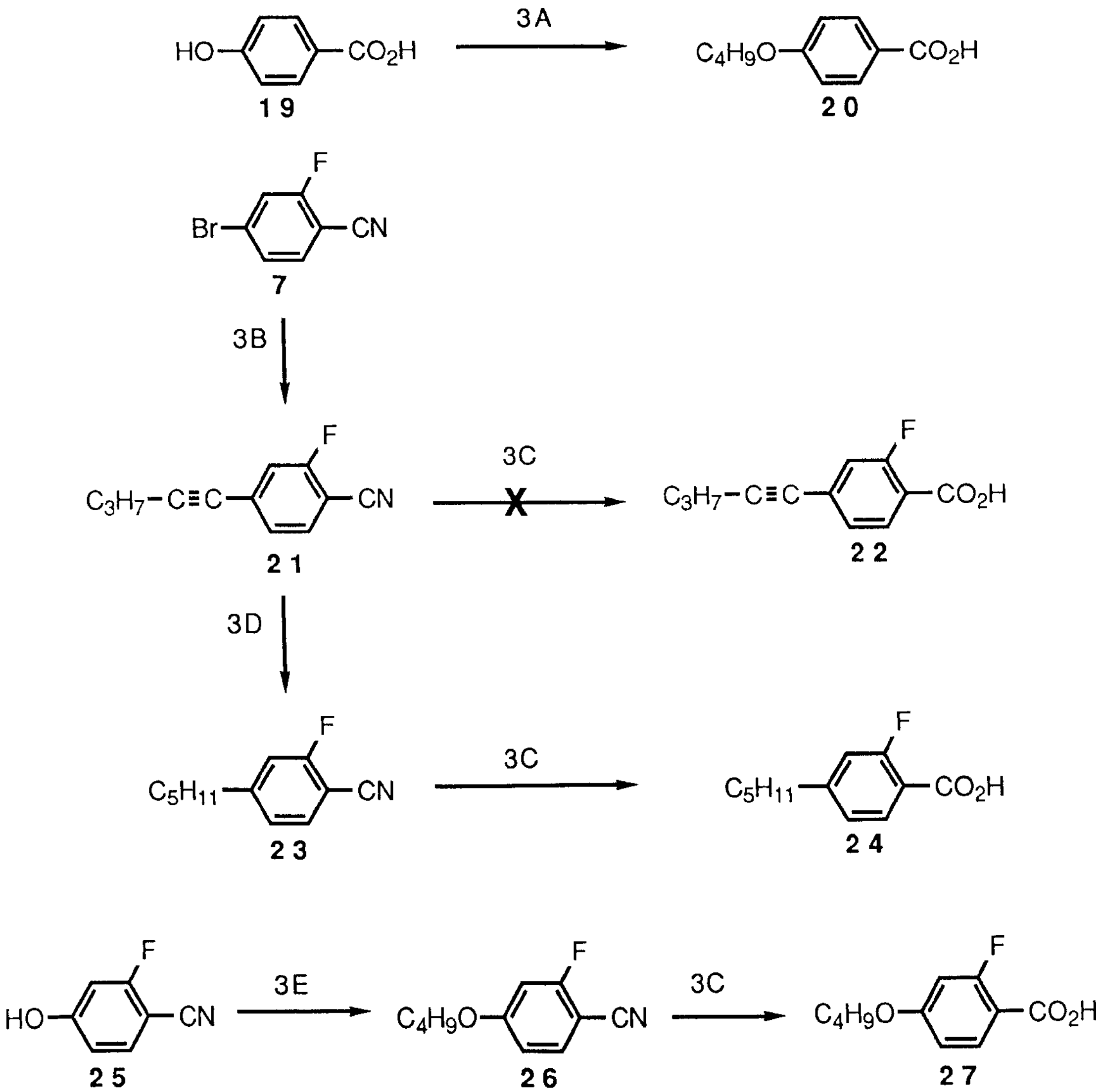
2B ...... Oxalyl chloride, DMF, benzene.

2C ...... 35% Ammonia.

2D ...... Thionyl chloride, DMF.

2E ...... $AlCl_3$, NaCl.

Scheme 3 (p 113-116)



3A ...... (i) C_4H_9Br, EtOH; (ii) water, NaOH; (iii) 36% HCl.

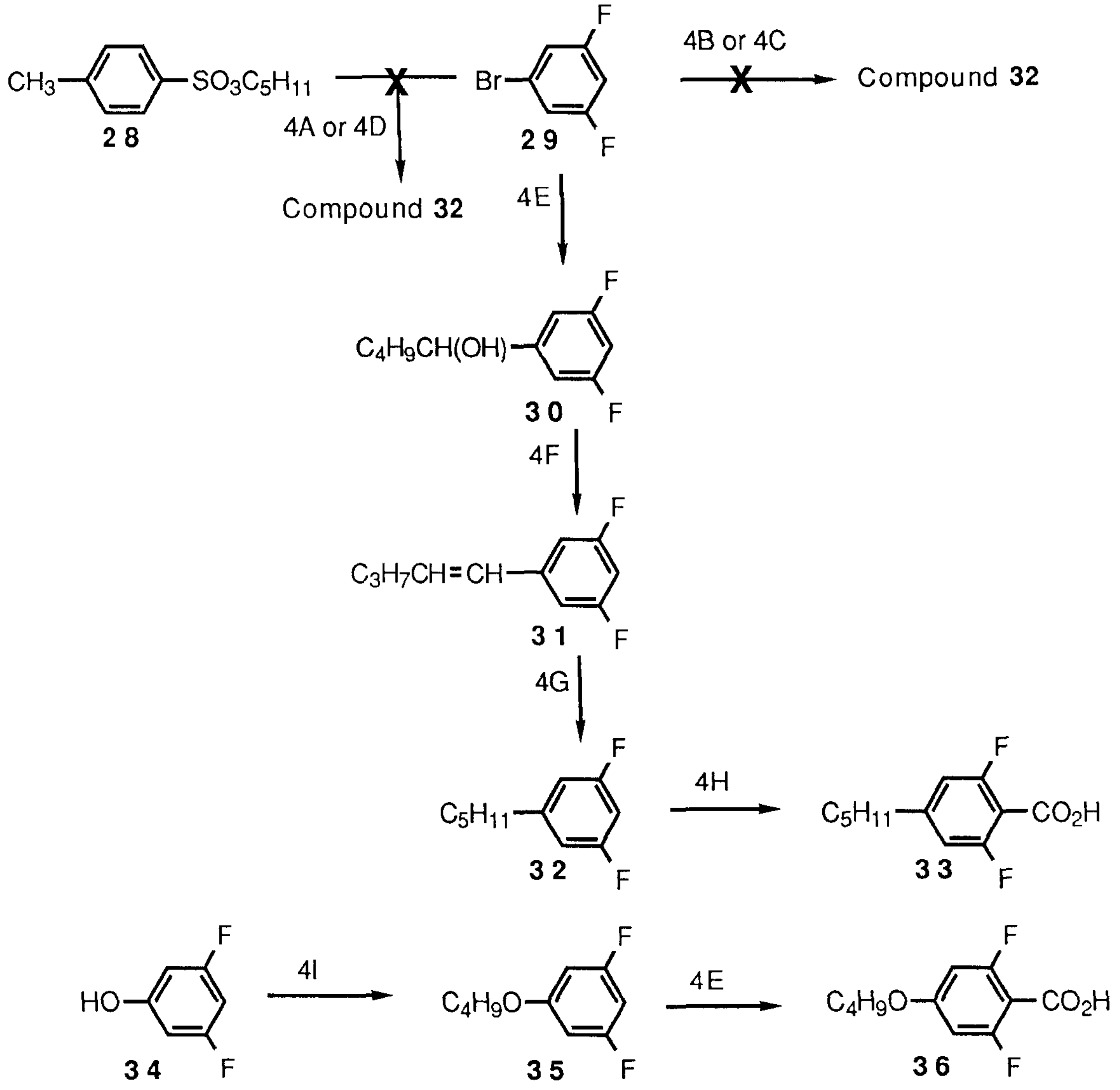
3B ...... (i) Pent-1-yne, nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, THF.

3C ...... conc. H_2SO_4, water, HOAc.

3D ...... 5% Pd/C, EtOH, H_2.

3E ...... C_4H_9Br, K_2CO_3, acetone.

Scheme 4 (p 116-120)



4A ...... (i) Mg, Et_2O; (ii) Li_2CuCl_4, THF.

4B ...... (i) $C_5H_{11}MgBr$, Et_2O; (ii) Ni(dppp)Cl_2, Et_2O.

4C ...... (i) Mg, THF; (ii) $C_5H_{11}Br$, CuCl, THF.

4D ...... (i) Mg, THF; (ii) CuCl, THF.

4E ...... (i) Mg, THF; (ii) C_4H_9CHO, Et_2O.

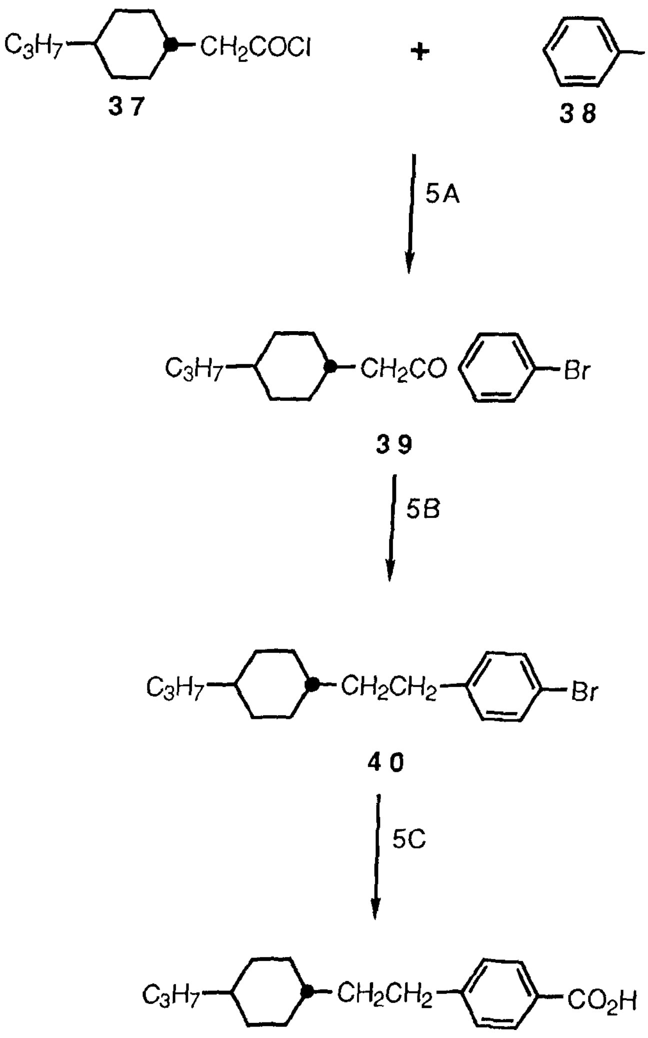
4F ...... P_2O_5, pentane.

4G ...... 5% Pd/C, pentane.

4H ...... (i) nBuLi, THF; (ii) CO_2 (solid), Et_2O.

4I ...... C_4H_9Br, K_2CO_3, acetone.

Scheme 5 (p 120-122)



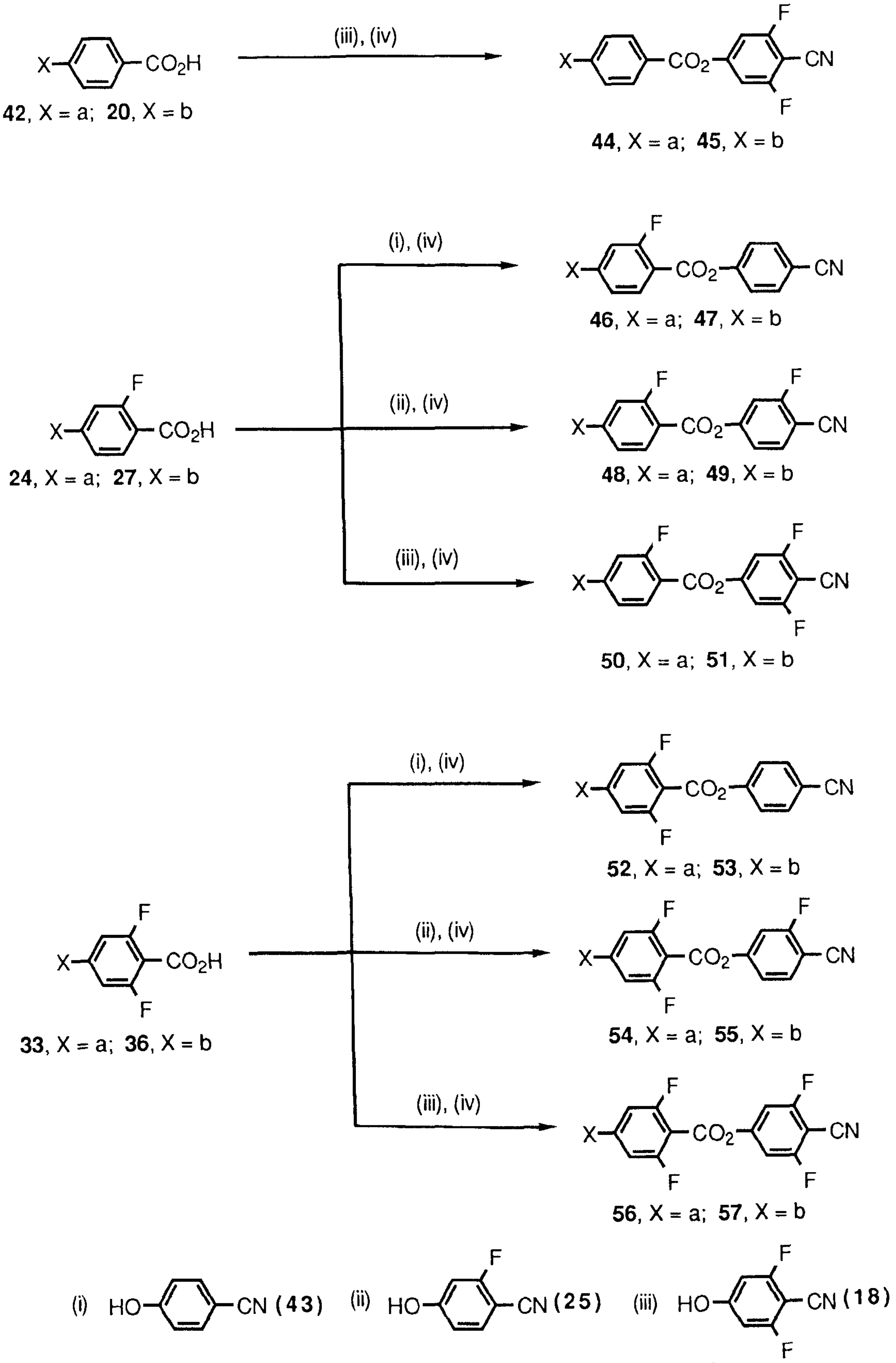
41

5A ...... Aluminium chloride.

5B ...... Et_3SiH, CF_3CO_2H.

5C ...... (i) nBuLi, THF; (ii) CO_2 (solid), Et_2O.

Scheme 6 (p 122-126)



42, X = a; **20**, X = b

44, X = a; **45**, X = b

24, X = a; **27**, X = b

46, X = a; **47**, X = b

48, X = a; **49**, X = b

50, X = a; **51**, X = b

33, X = a; **36**, X = b

52, X = a; **53**, X = b

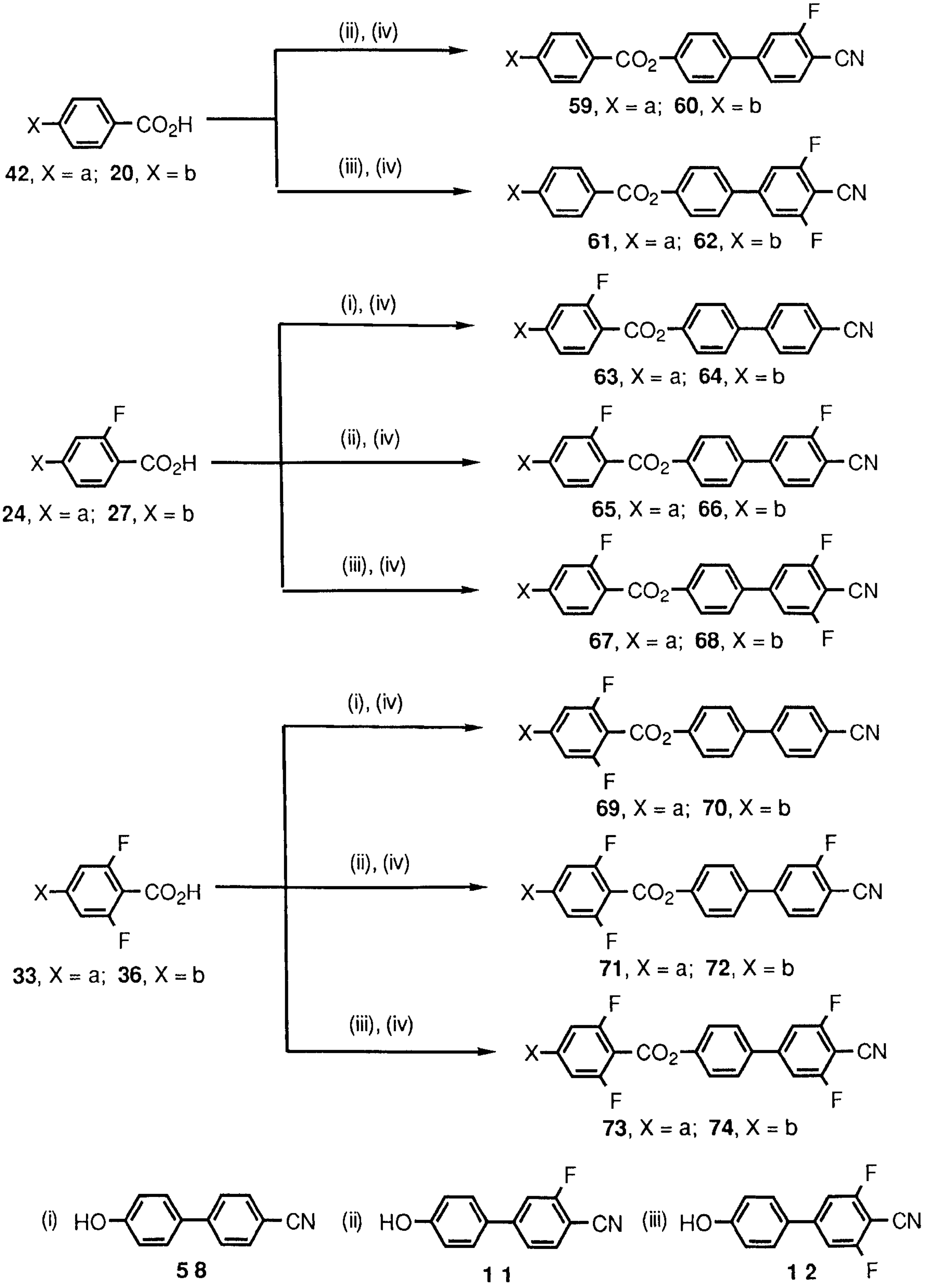
54, X = a; **55**, X = b

56, X = a; **57**, X = b

(iv) *N,N*-Dicyclohexylcarbodi-imide, 4-(*N*-pyrrolidino)pyridine, CH_2Cl_2.

Key: a = C_5H_{11}, b = C_4H_9O

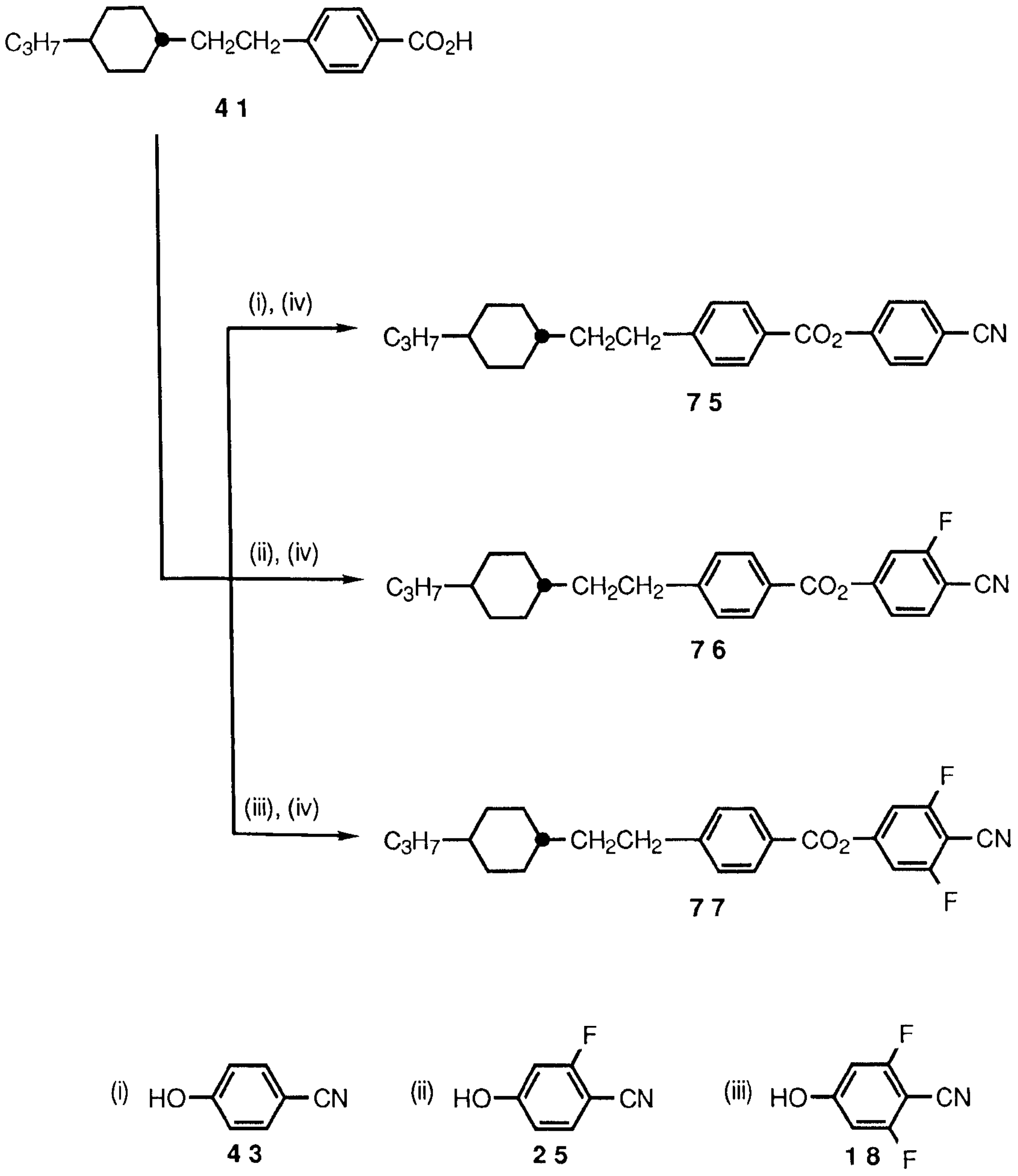
Scheme 7 (p 122, 127-131)



(iv) *N,N*-Dicyclohexylcarbodi-imide, 4-(*N*-pyrrolidino)pyridine, CH_2Cl_2.

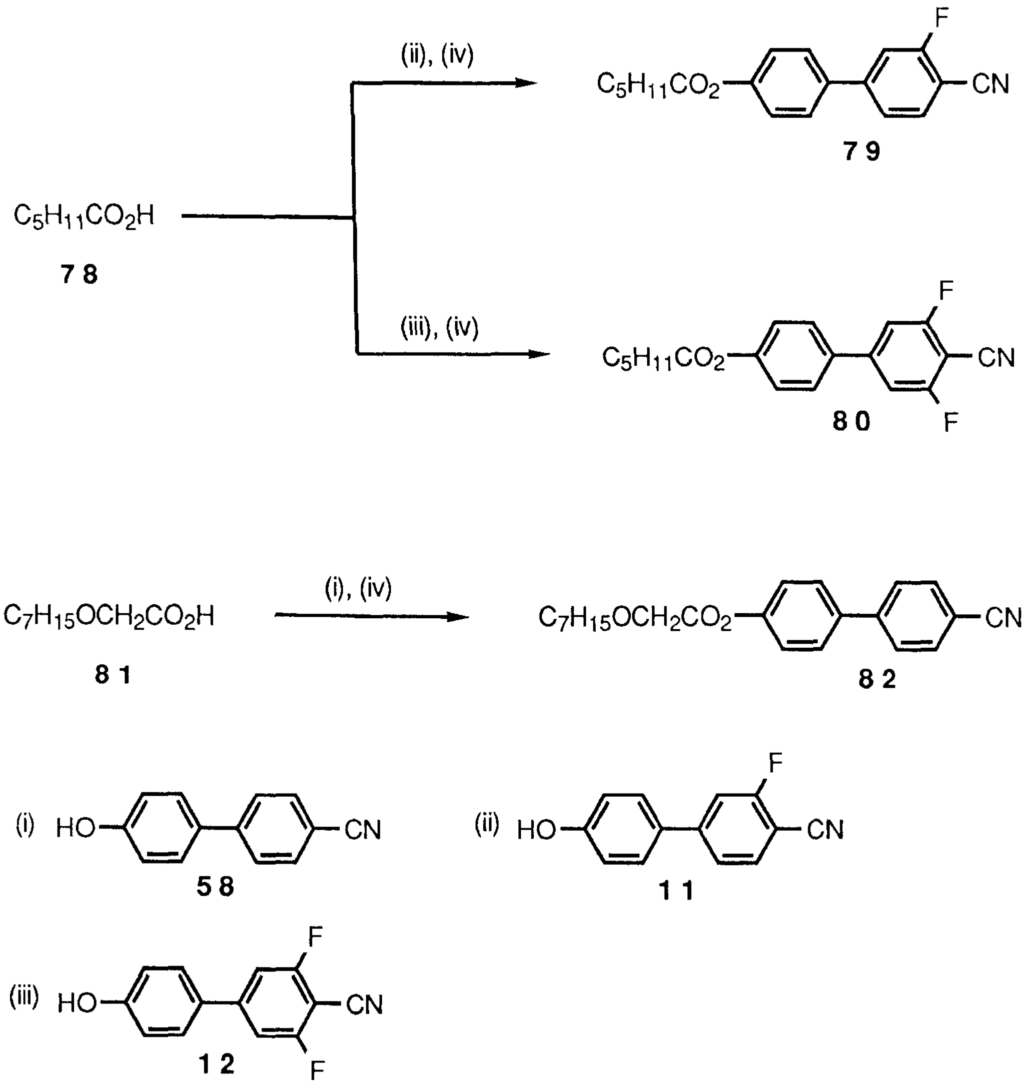
Key: a = C_5H_{11}, b = C_4H_9O

Scheme 8 (p 122, 131, 132)



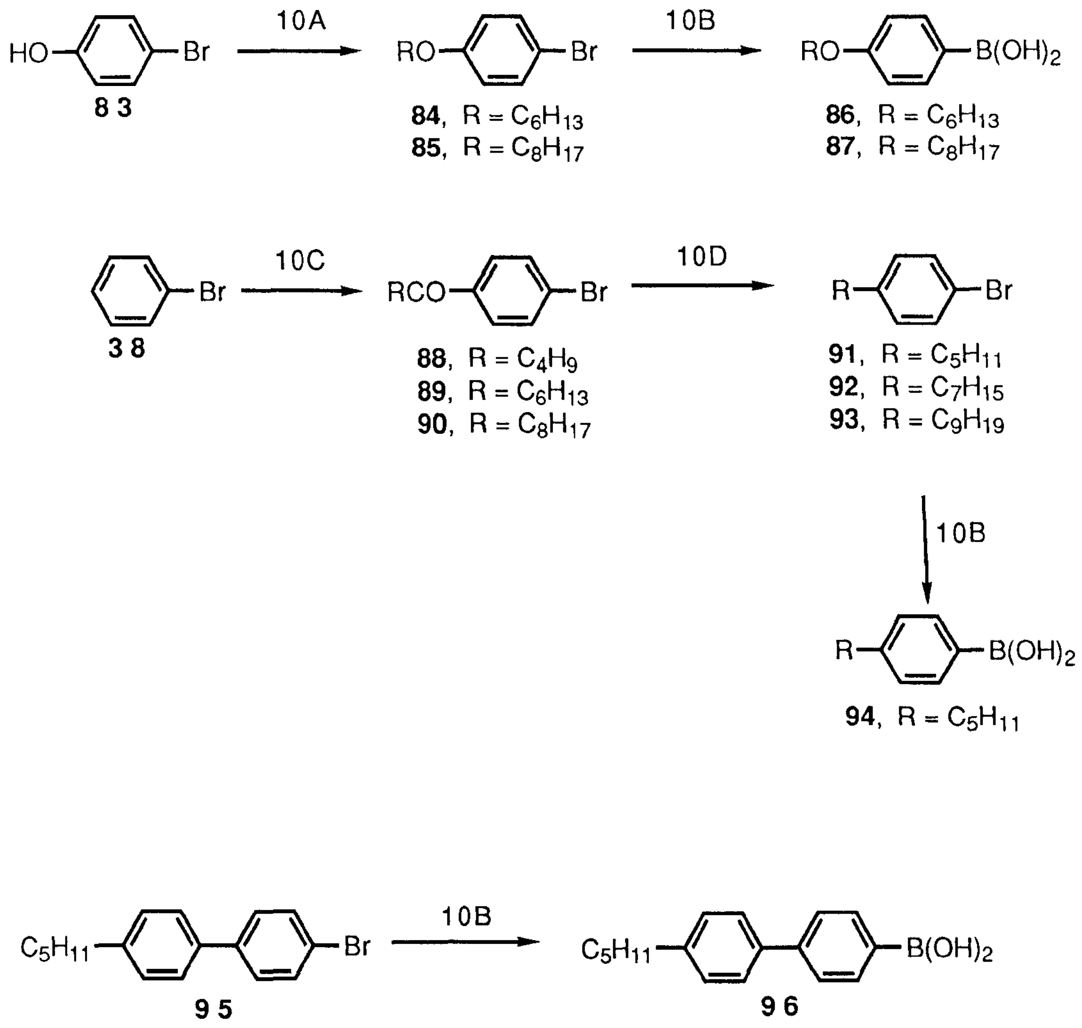
(iv) *N,N*-Dicyclohexylcarbodi-imide, 4-(*N*-pyrrolidino)pyridine, CH_2Cl_2.

Scheme 9 (p 122, 132, 133)



(iv) *N,N*-Dicyclohexylcarbodi-imide, 4-(*N*-pyrrolidino)pyridine, CH_2Cl_2.

Scheme 10 (p 134-138)



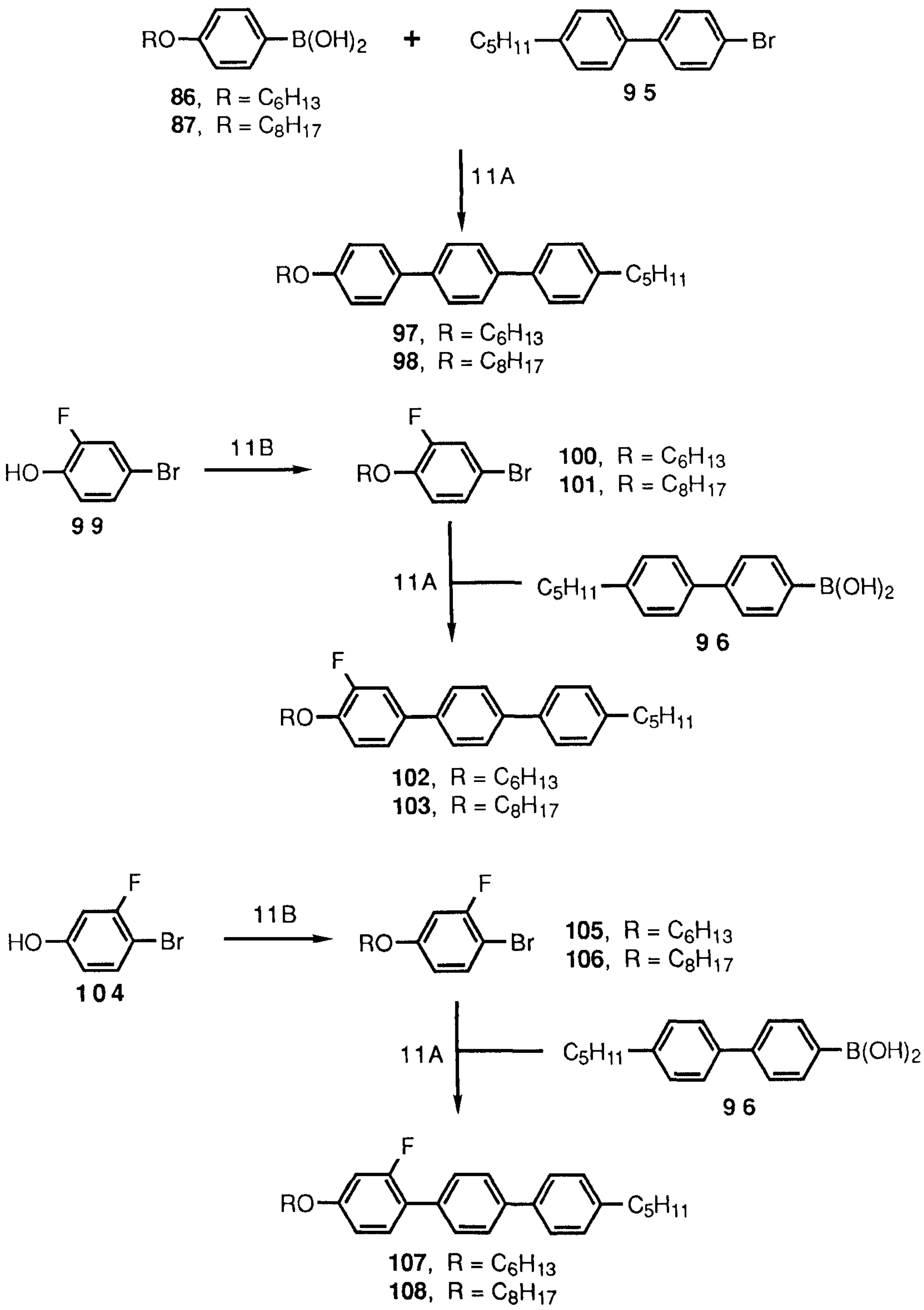
10A ...... RBr, K_2CO_3, acetone.

10B ...... (i) Mg, THF; (ii) $(^{i}PrO)_3B$, THF; (iii) 10% HCl.

10C ...... RCOCl, aluminium chloride.

10D ...... Hydrazine hydrate, KOH, diethylene glycol.

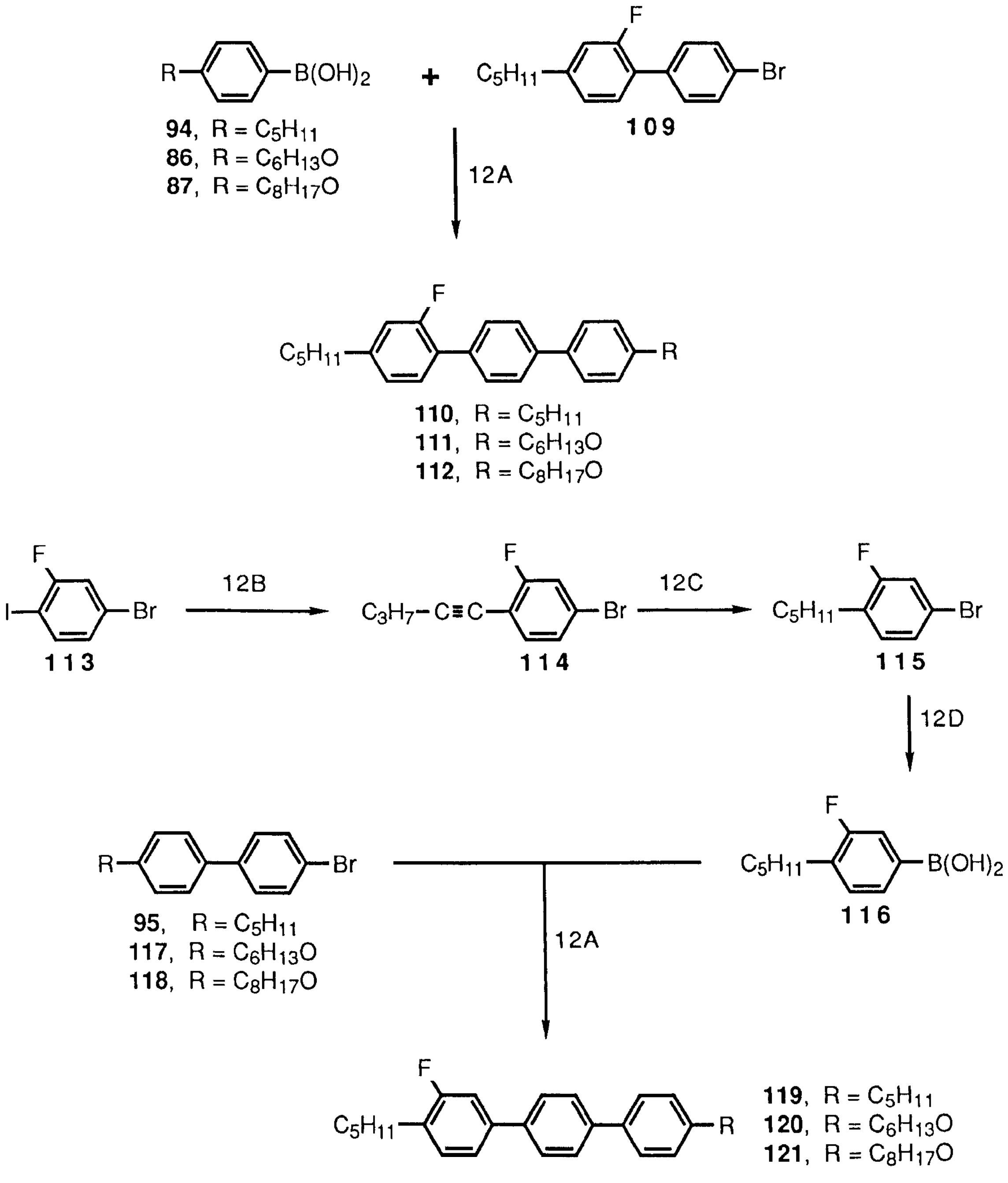
Scheme 11 (p 138-142)



11A ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

11B ...... RBr, K_2CO_3, acetone.

Scheme 12 (p 142-146)



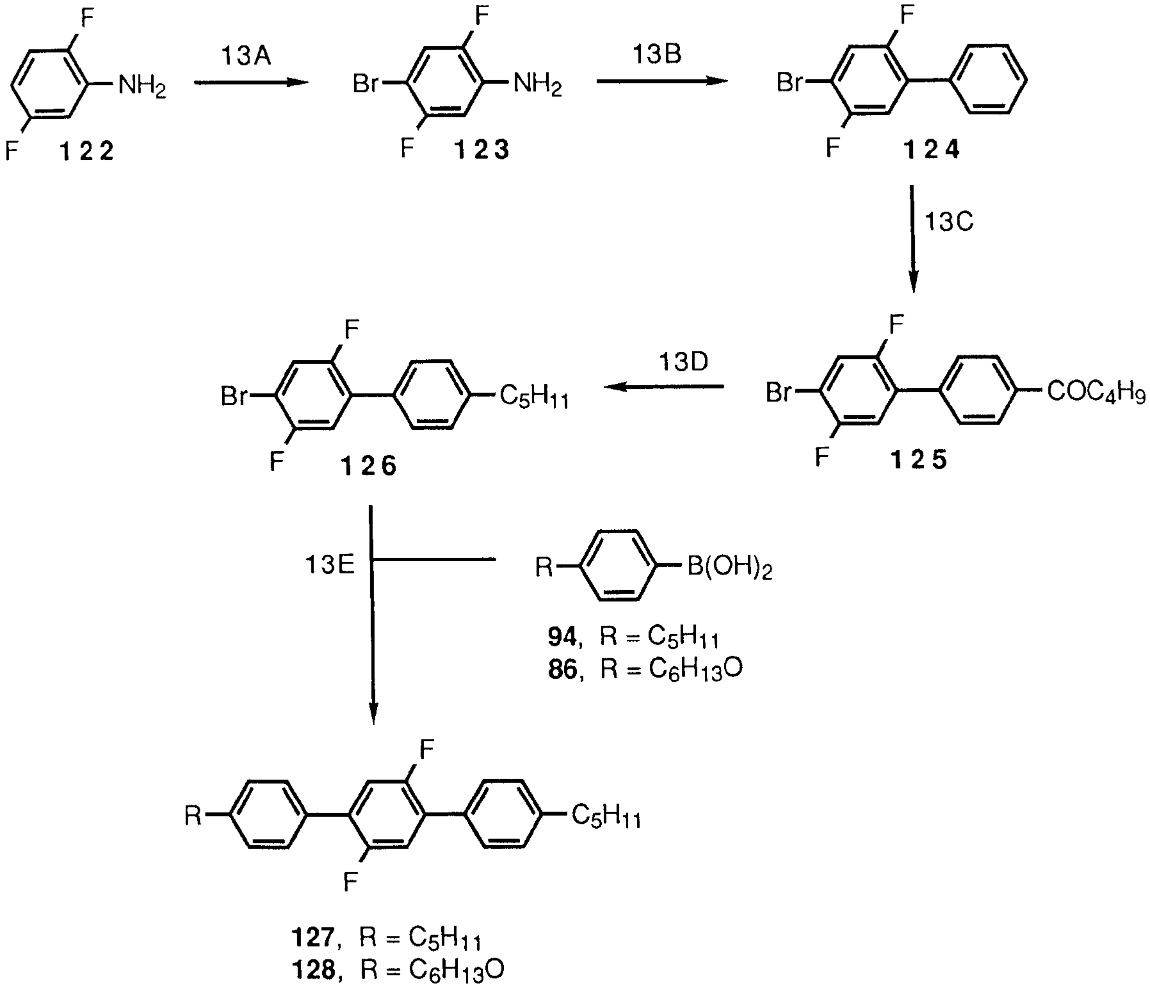
12A ...... Pd(PPh$_3$)$_4$, benzene, EtOH, 2M-Na$_2$CO$_3$.

12B ...... (i) Pent-1-yne, nBuLi, THF; (ii) ZnCl$_2$, THF; (iii) Pd(PPh$_3$)$_4$, THF.

12C ...... PtO$_2$, EtOH, H$_2$.

12D ...... (i) Mg, THF; (ii) (^{i}PrO)$_3$B, THF; (iii) 10% HCl.

Scheme 13 (p 146-149)



13A ...... NBS, CH_2Cl_2.

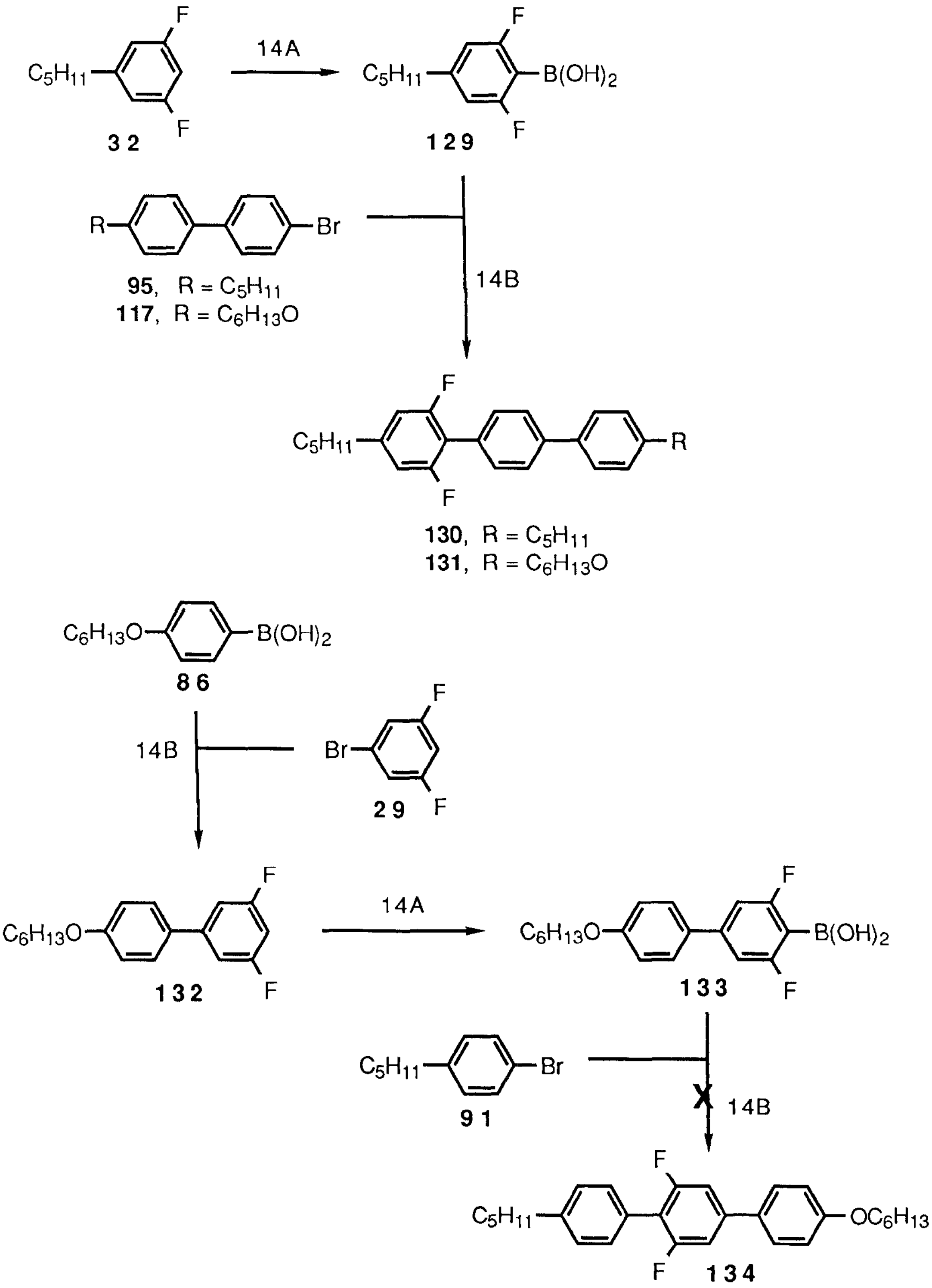
13B ...... Isopentyl nitrite, benzene.

13C ...... C_4H_9COCl, aluminium chloride, CH_2Cl_2.

13D ...... Et_3SiH, CF_3CO_2H.

13E ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

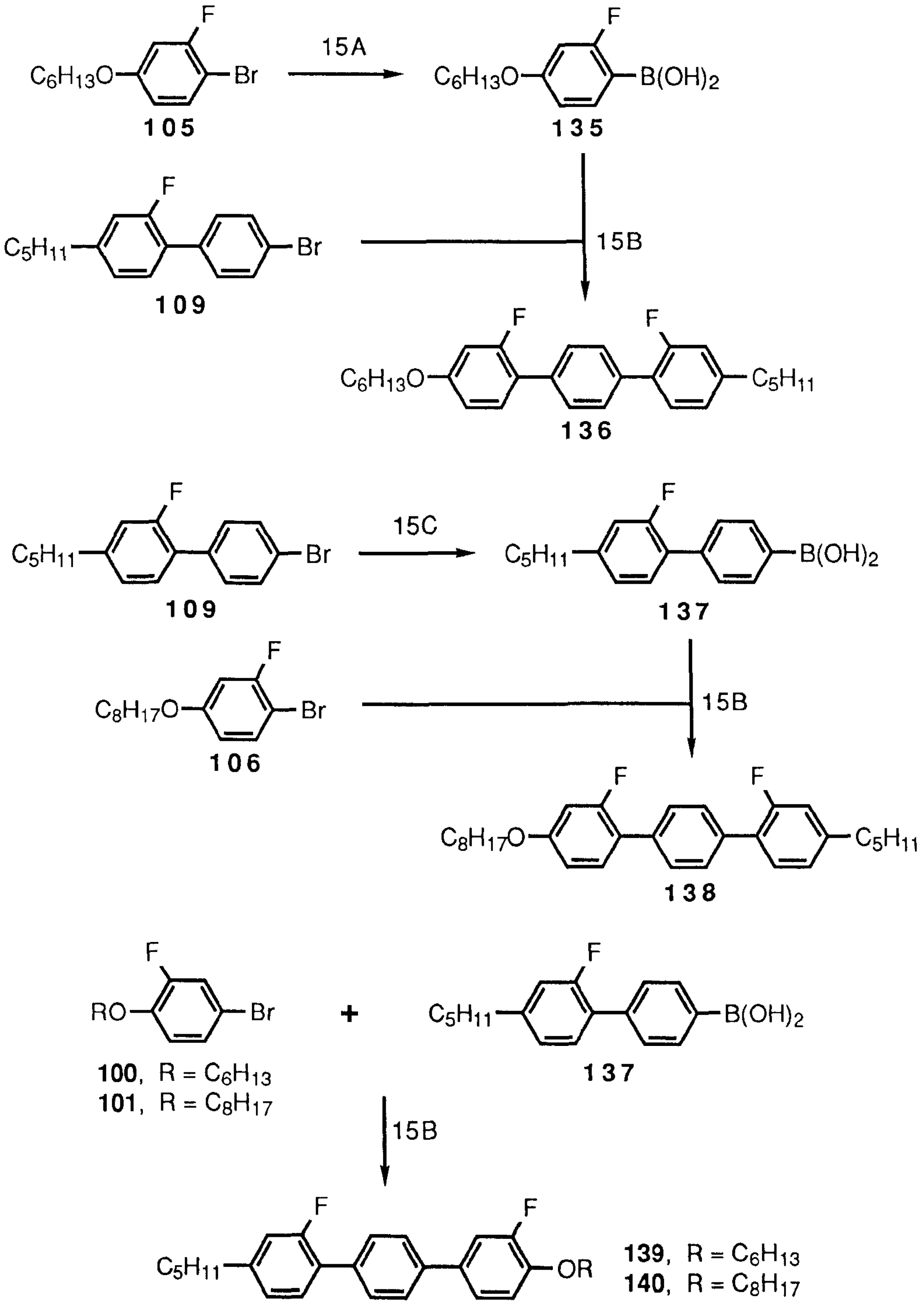
Scheme 14 (p 149-151)



14A ...... (i) nBuLi, THF; (ii) $(^iPrO)_3B$, THF; (iii) 10% HCl.

14B ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 15 (p 152-154)

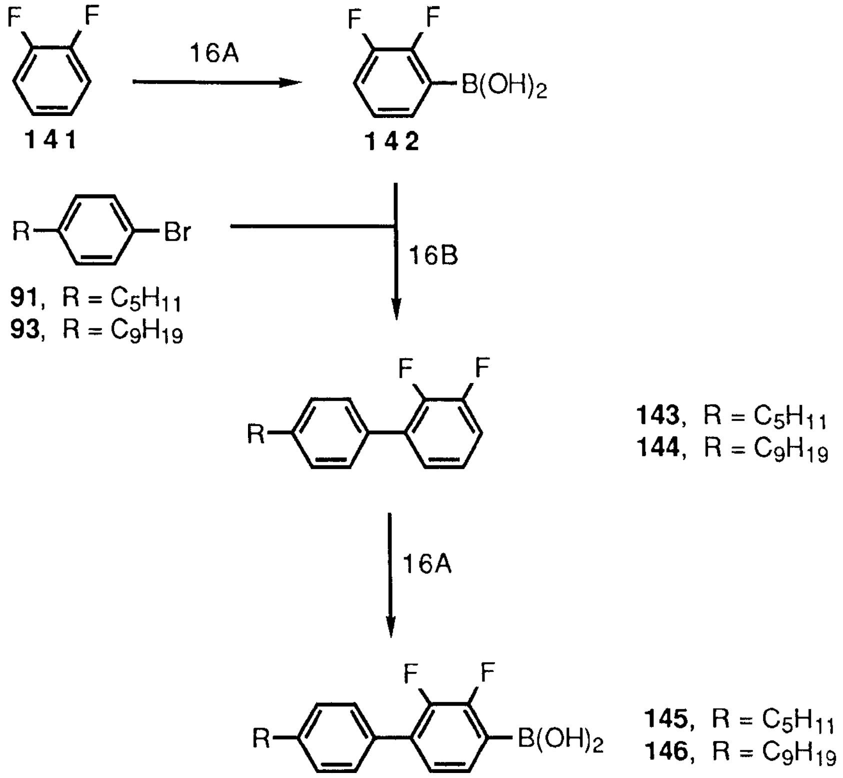


15A ...... (i) nBuLi, THF; (ii) (^{i}PrO)$_3$B, THF; (iii) 10% HCl.

15B ...... Pd(PPh$_3$)$_4$, benzene, EtOH, 2M-Na$_2$CO$_3$.

15C ...... (i) Mg, THF; (ii) (^{i}PrO)$_3$B, THF; (iii) 10% HCl.

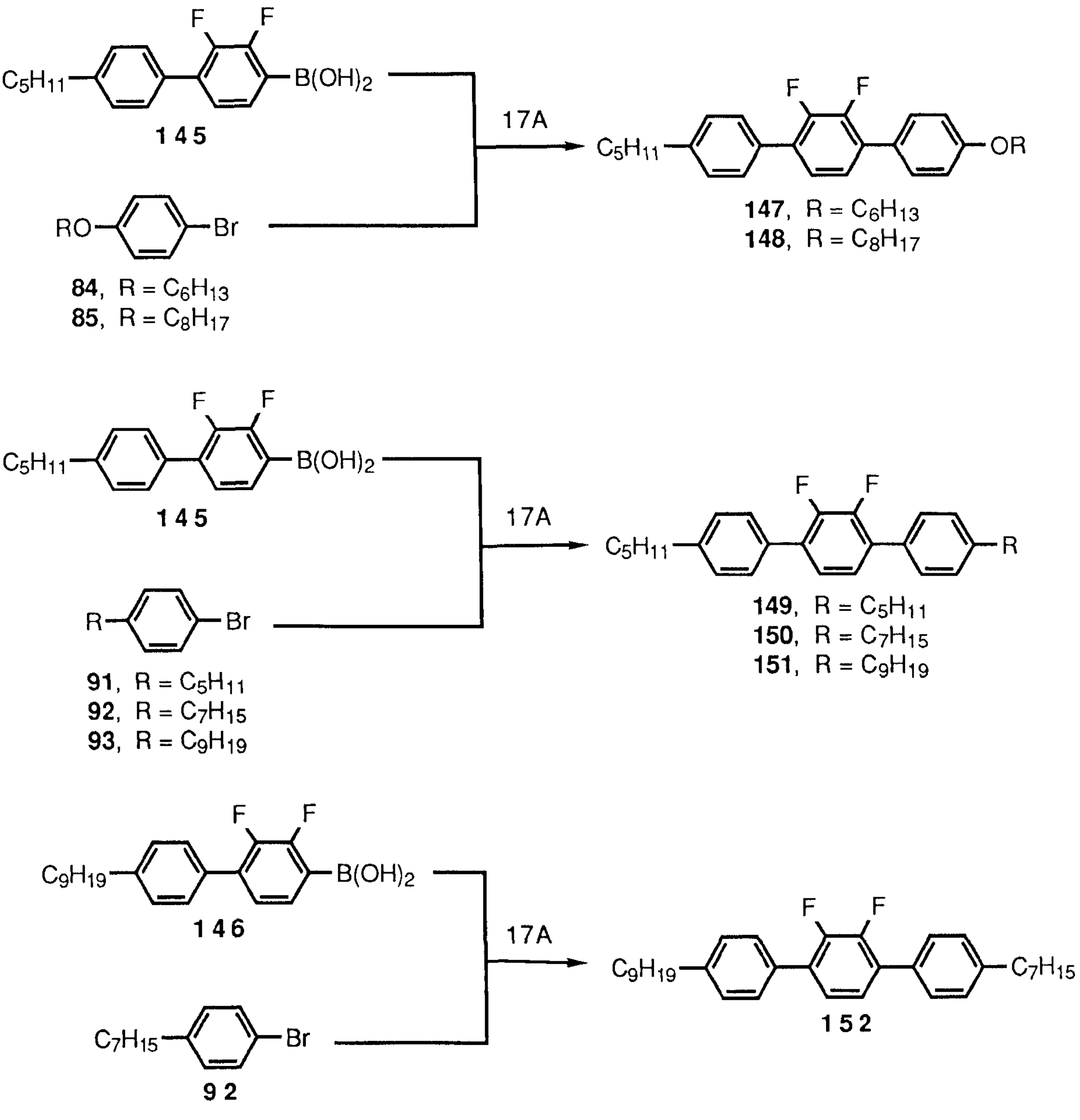
Scheme 16 (p 154-156)



16A ...... (i) nBuLi, THF; (ii) (^{i}PrO)$_3$B, THF; (iii) 10% HCl.

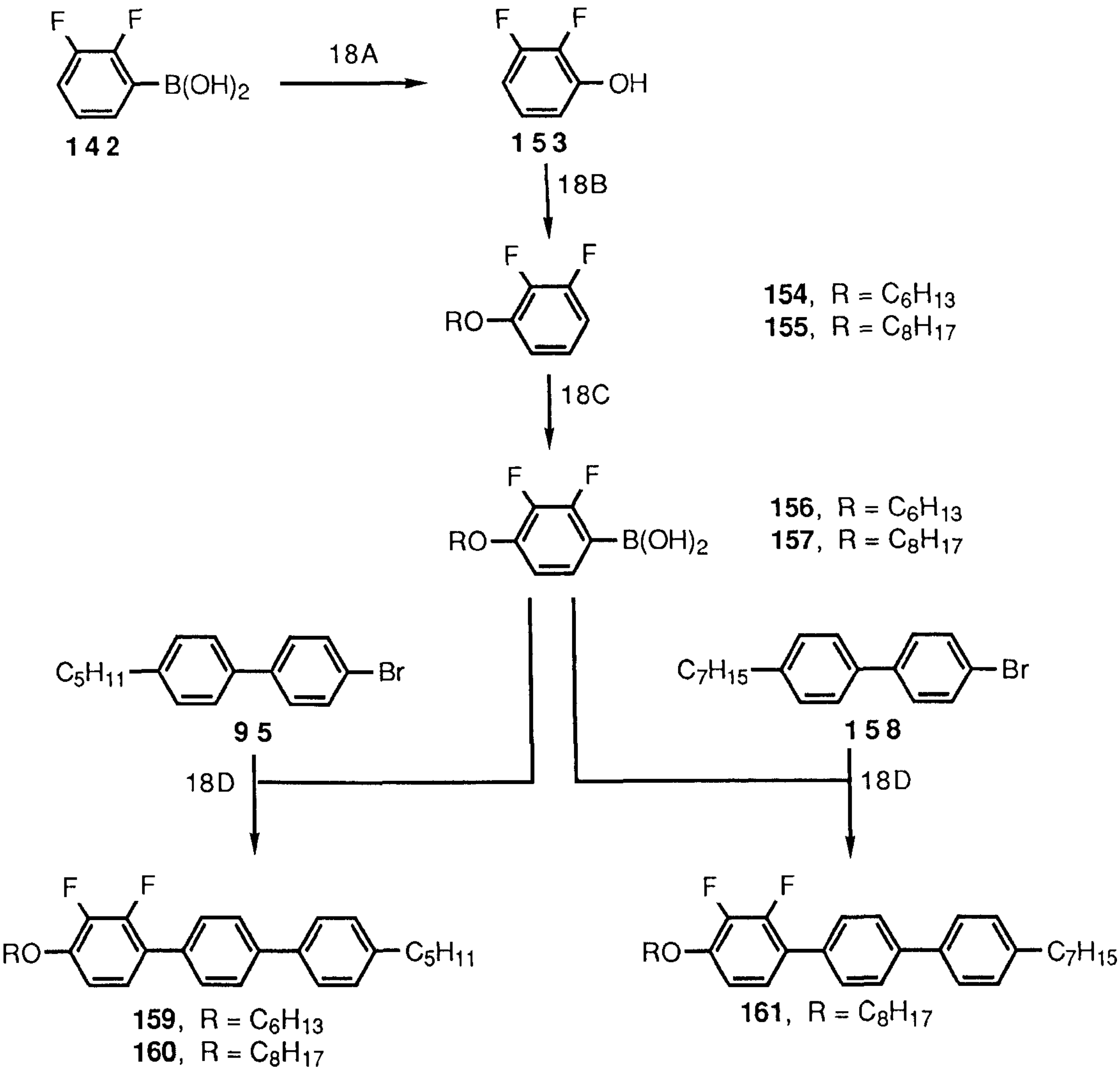
16B ...... Pd(PPh$_3$)$_4$, benzene, EtOH, 2M-Na$_2$CO$_3$.

Scheme 17 (p 156-158)



17A ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 18 (p 159-162)



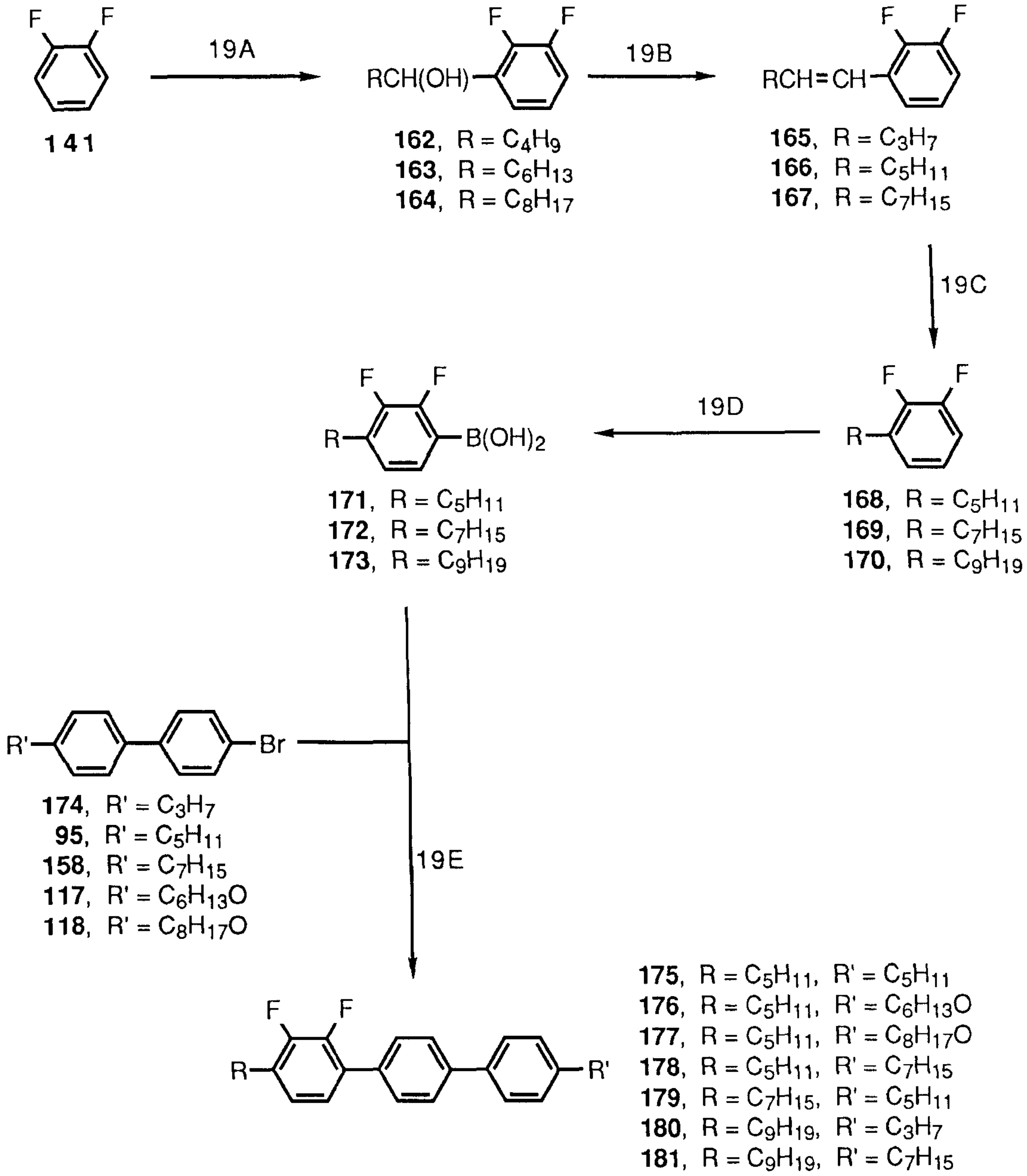
18A ...... 10% H_2O_2, Et_2O.

18B ...... RBr, K_2CO_3, acetone.

18C ...... (i) nBuLi, THF; (ii) ($^iPrO)_3B$, THF; (iii) 10% HCl.

18D ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 19 (p 162-168)



19A ...... (i) nBuLi, THF; (ii) RCHO, THF.

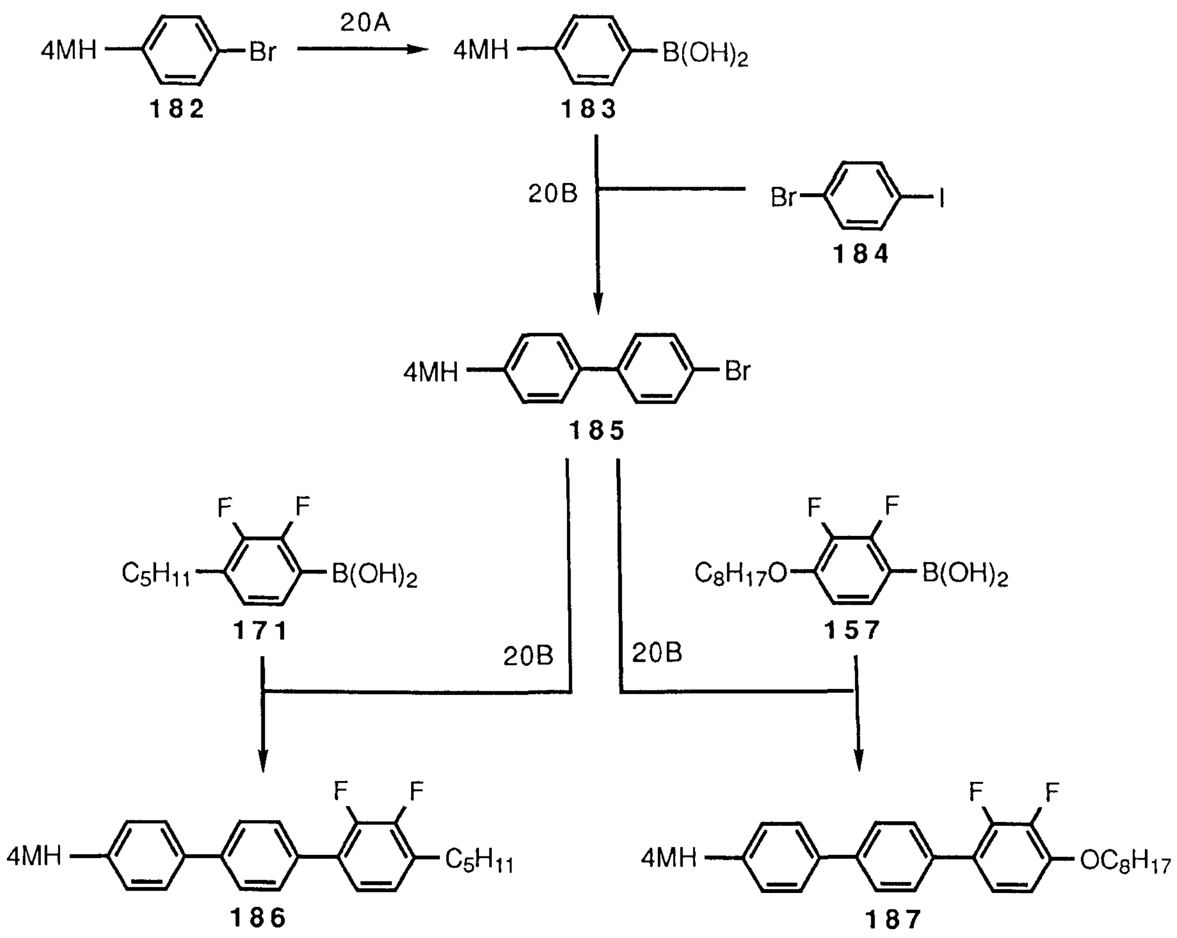
19B ...... P_2O_5, pentane.

19C ...... 5% Pd/C, pentane, H_2.

19D ...... (i) nBuLi, THF; (ii) $(^iPrO)_3B$, THF; (iii) 10% HCl.

19E ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 20 (p 169, 170)

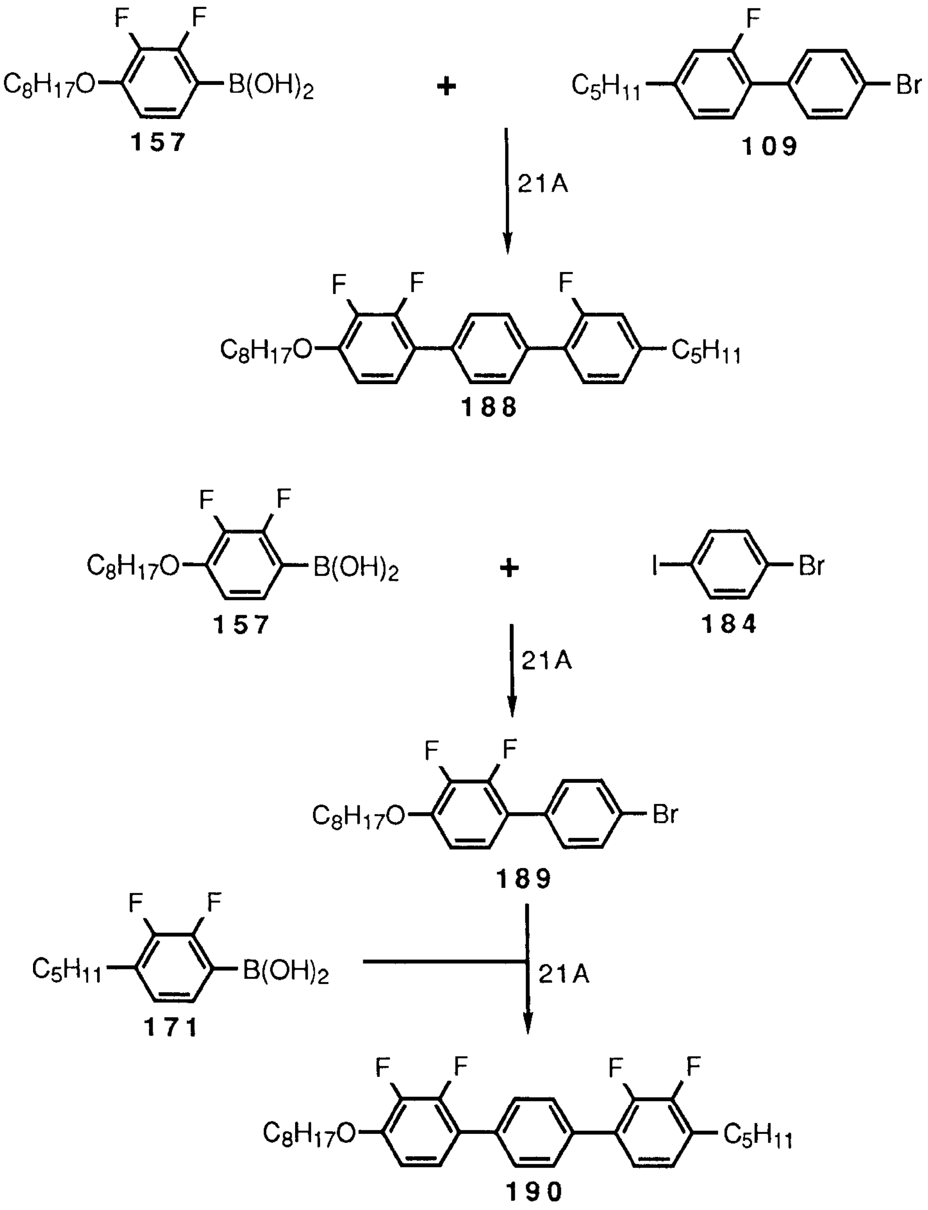


4MH = (±)-4-Methylhexyl

20A ...... (i) nBuLi, THF; (ii) (^{i}PrO)$_3$B, THF; (iii) 10% HCl.

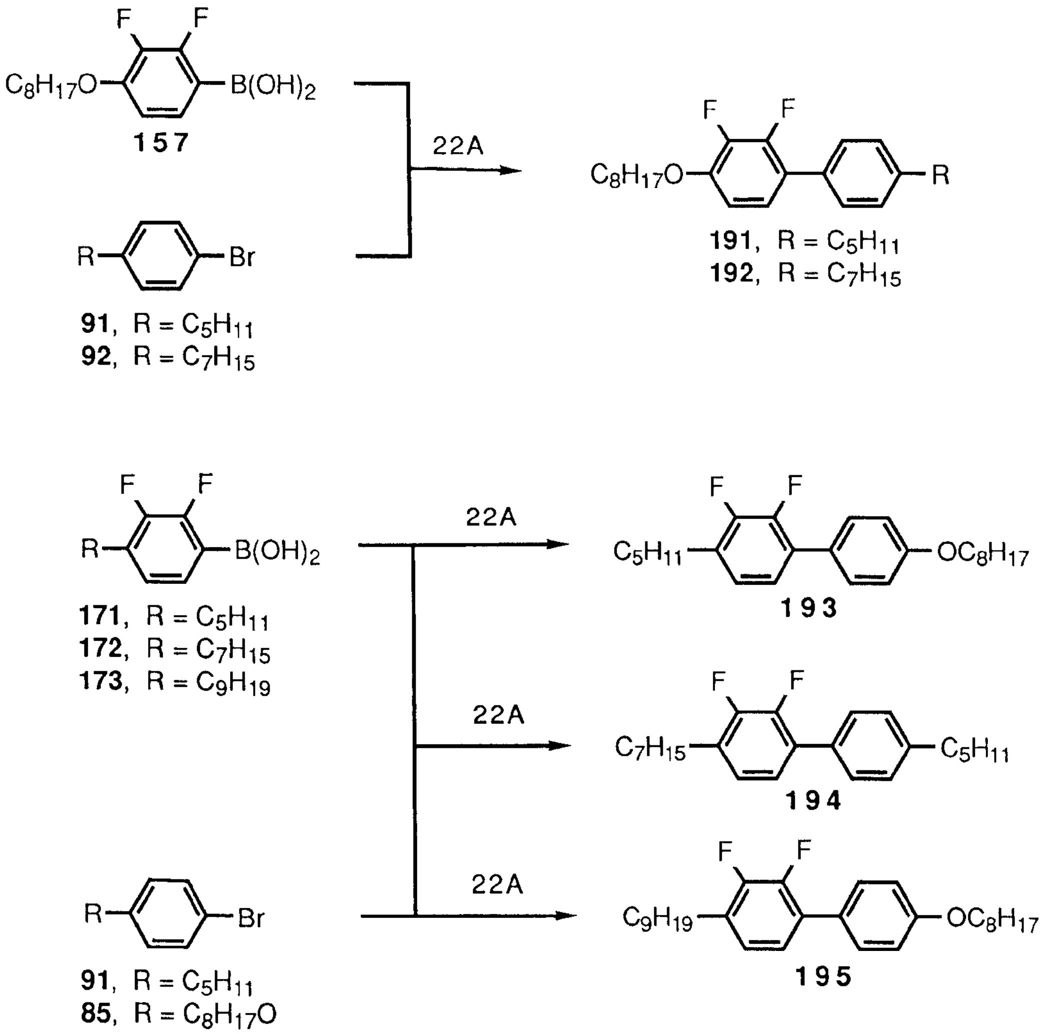
20B ...... Pd(PPh$_3$)$_4$, benzene, EtOH, 2M-Na$_2$CO$_3$.

Scheme 21 (p 170-172)



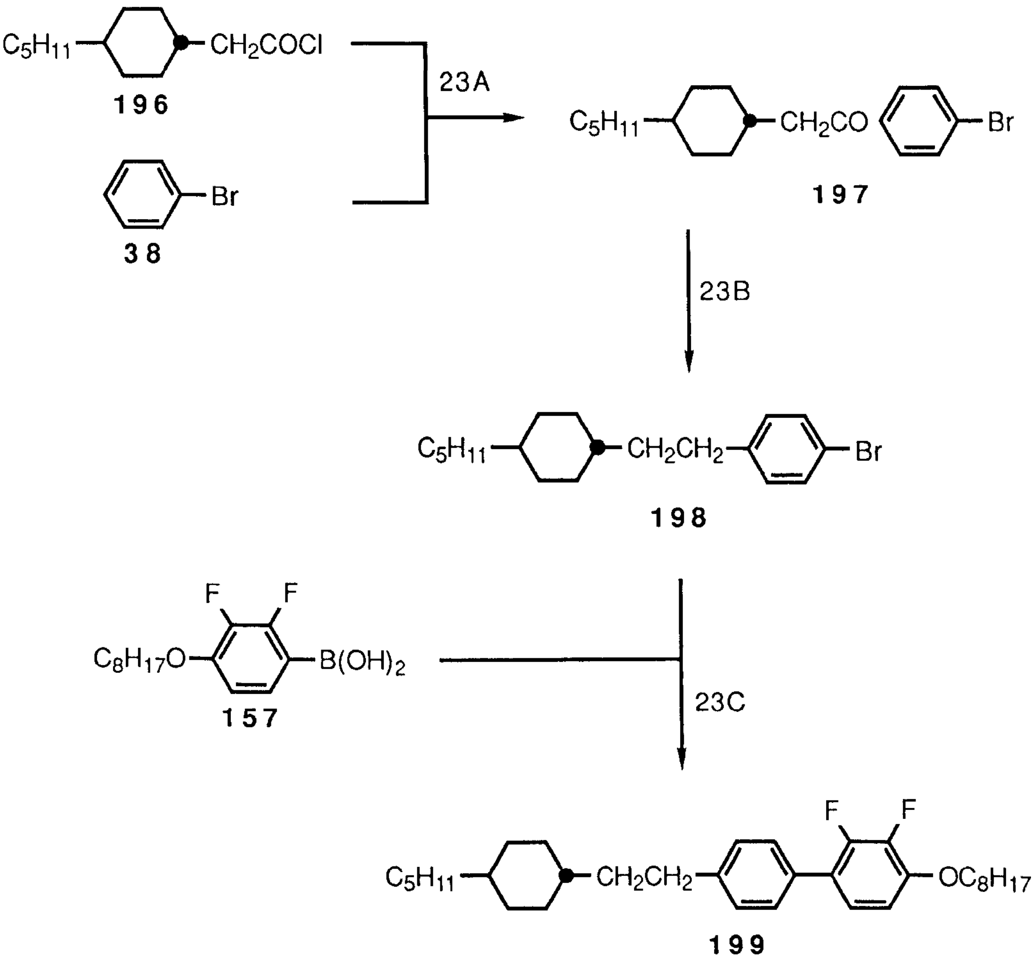
21A ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 22 (p 172-174)



22A ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3

Scheme 23 (p 174, 175)

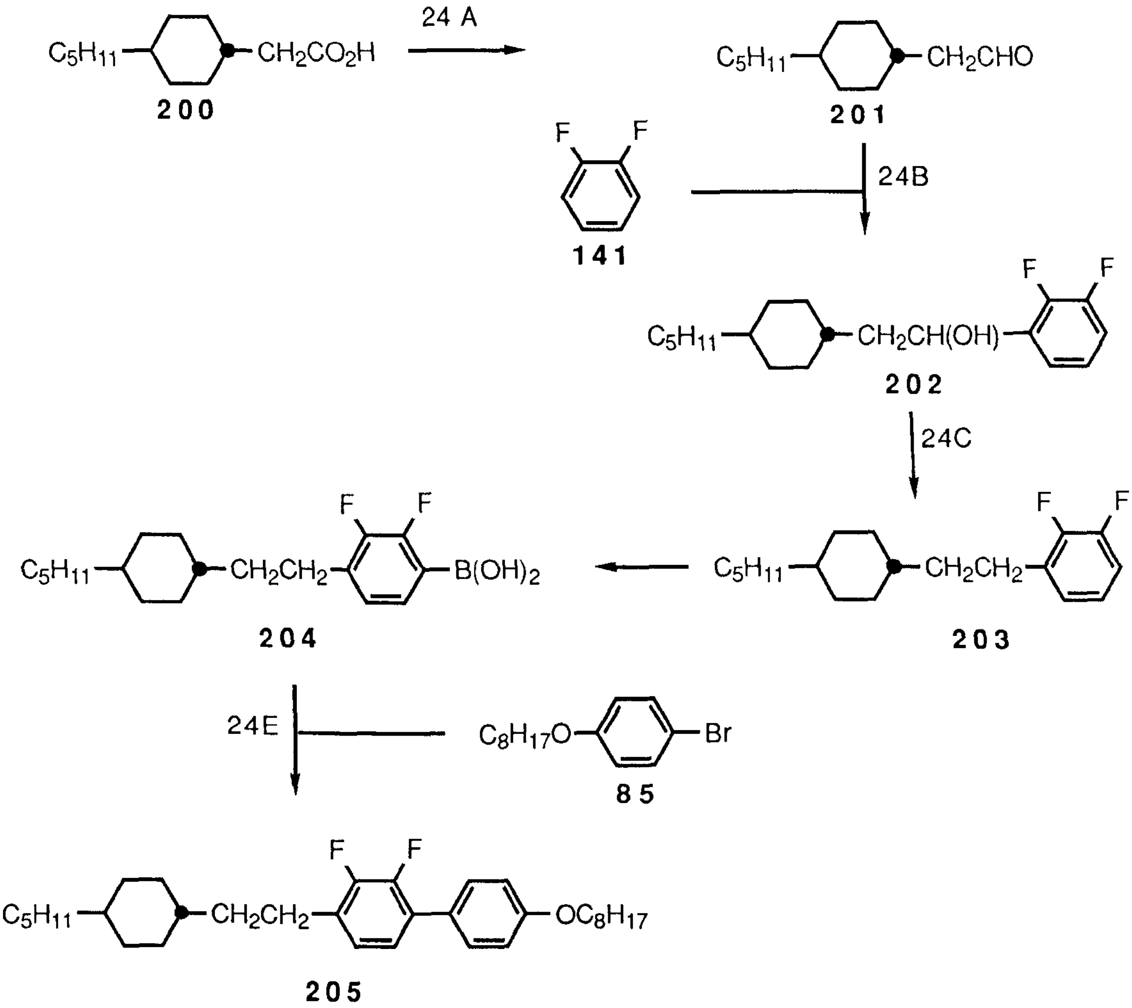


23A ...... Aluminium chloride.

23B ...... Et_3SiH, CF_3CO_2H.

23C ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 24 (p 175-178)



24A ...... (i) Oxalyl chloride, DMF, pyridine; (ii) $LiAlH(O^tBu)_3$, CuI.

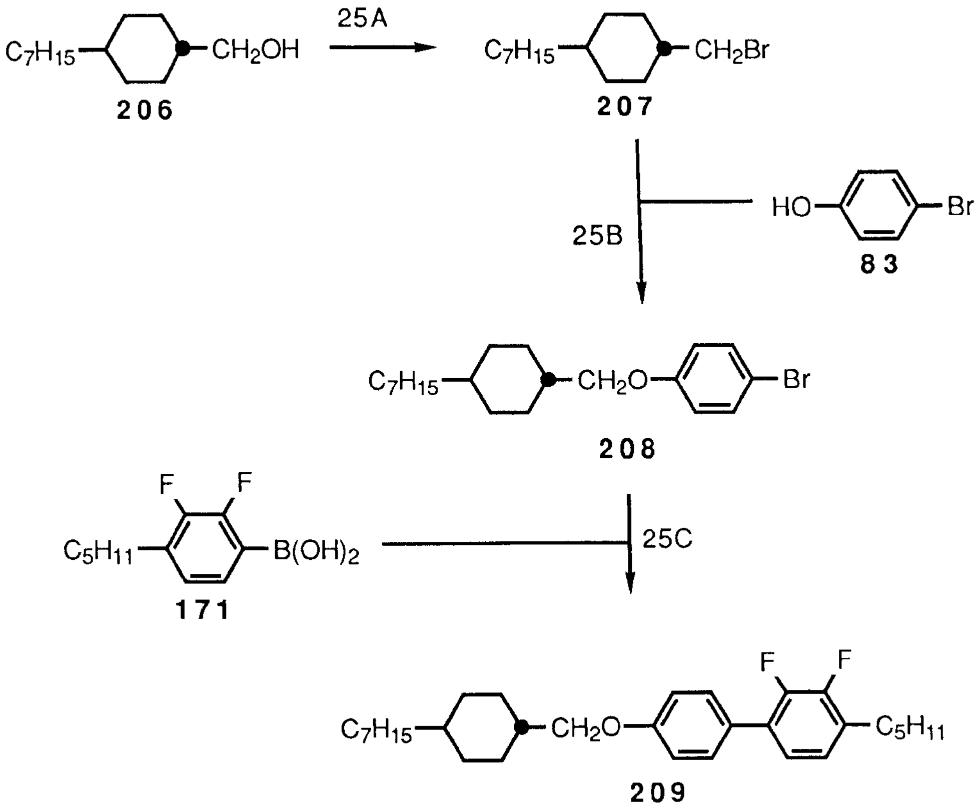
24B ...... (i) nBuLi, THF; (ii) compound **201**, THF.

24C ...... Et_3SiH, CF_3CO_2H or (i) P_2O_5, pentane; (ii) 5% Pd/C, pentane (see text).

24D ...... (i) nBuLi, THF; (ii) $(^iPrO)_3B$, THF; (iii) 10% HCl.

24E ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 25 (p 178, 179)

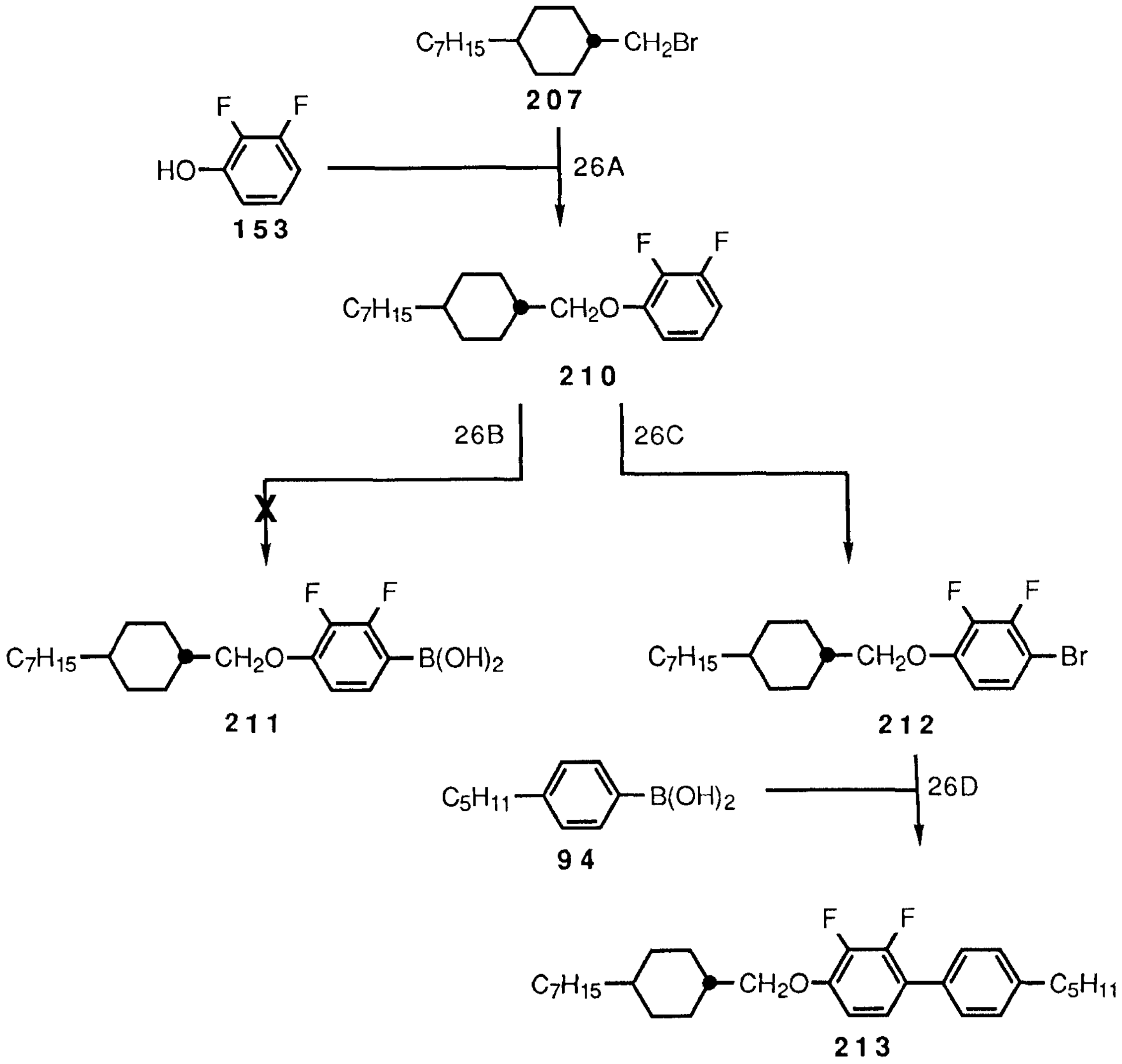


25A ...... 49% HBr, 98% H_2SO_4.

25B ...... K_2CO_3, cyclohexanone.

25C ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 26 (p 179-181)



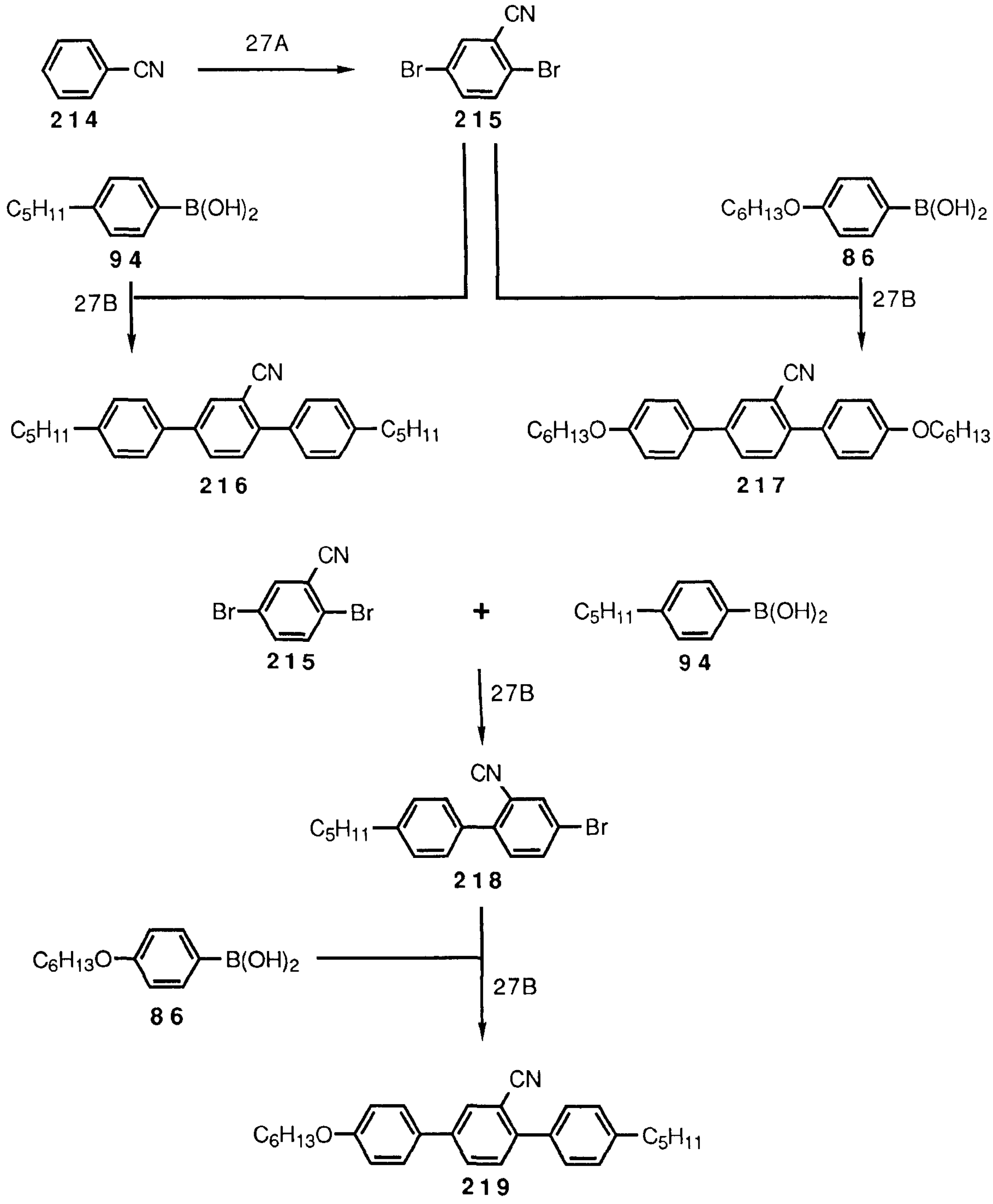
26A ...... K_2CO_3, cyclohexanone.

26B ...... (i) nBuLi, THF; (ii) $(^iPrO)_3B$, THF; (iii) 10% HCl.

26C ...... Br_2, $CHCl_3$.

26D ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

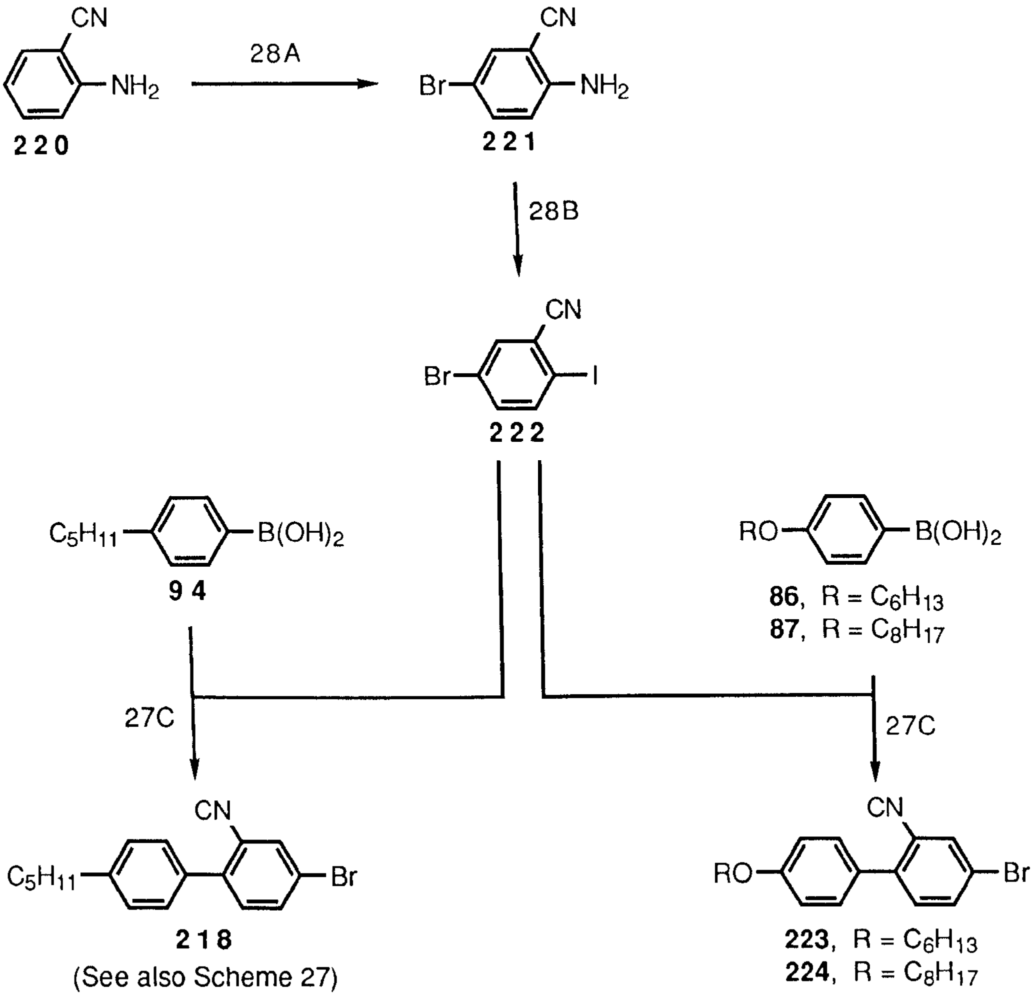
Scheme 27 (p 181-183)



27A ...... $AlCl_3$, Br_2.

27B ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 28 (p 183-186)

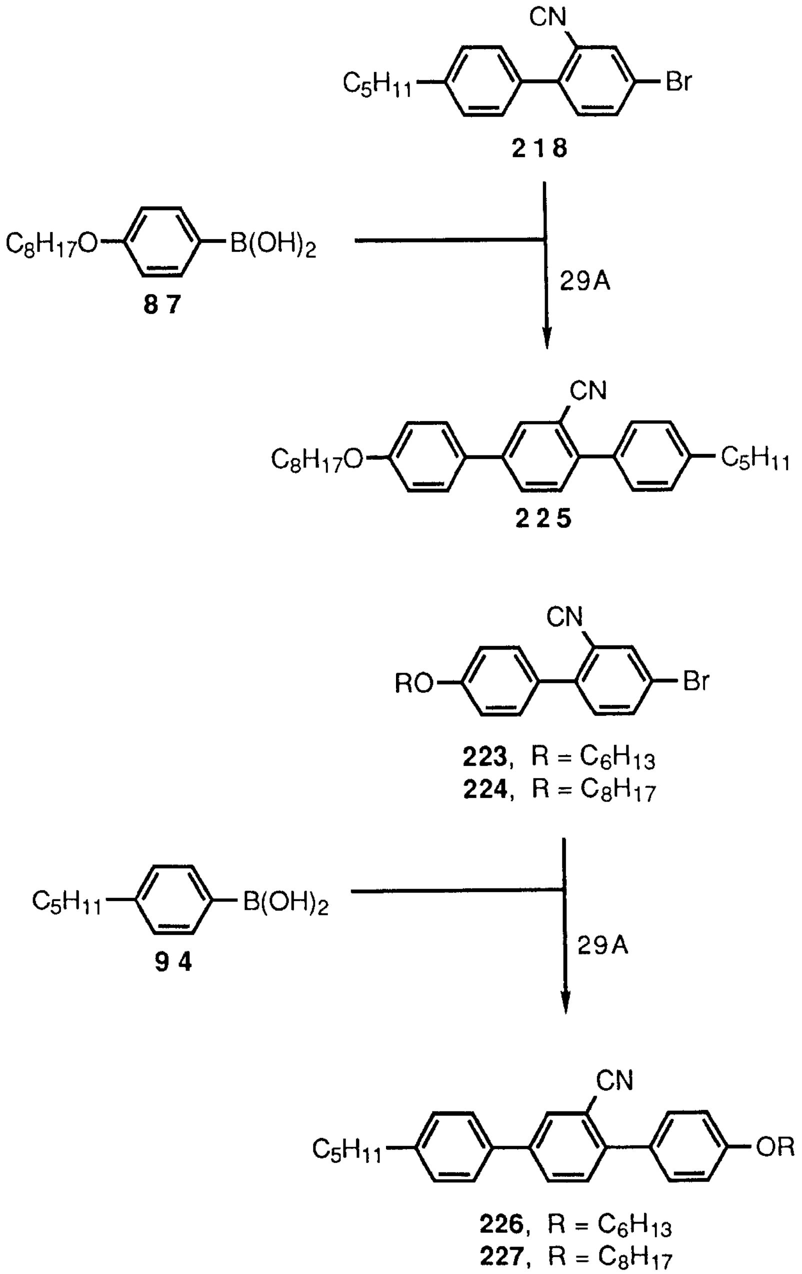


28A ...... NBS, CH_2Cl_2.

28B ...... (i) $NaNO_2$, 36% HCl; (ii) KI.

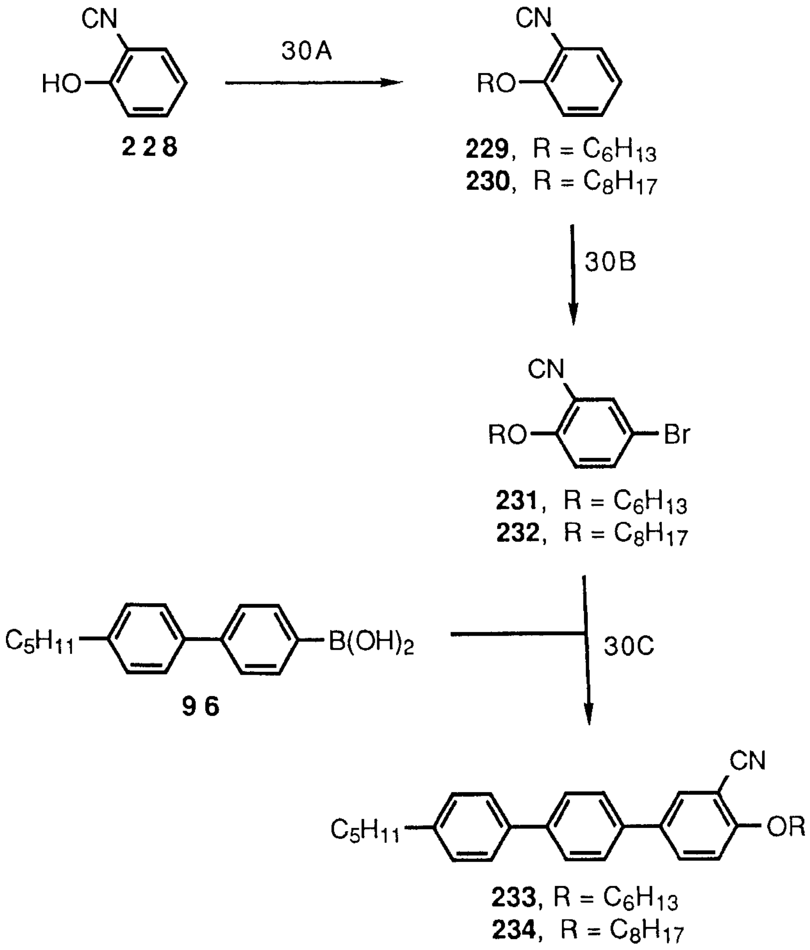
28C ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 29 (p 186, 187)



29A ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3

Scheme 30 (p 187-190)

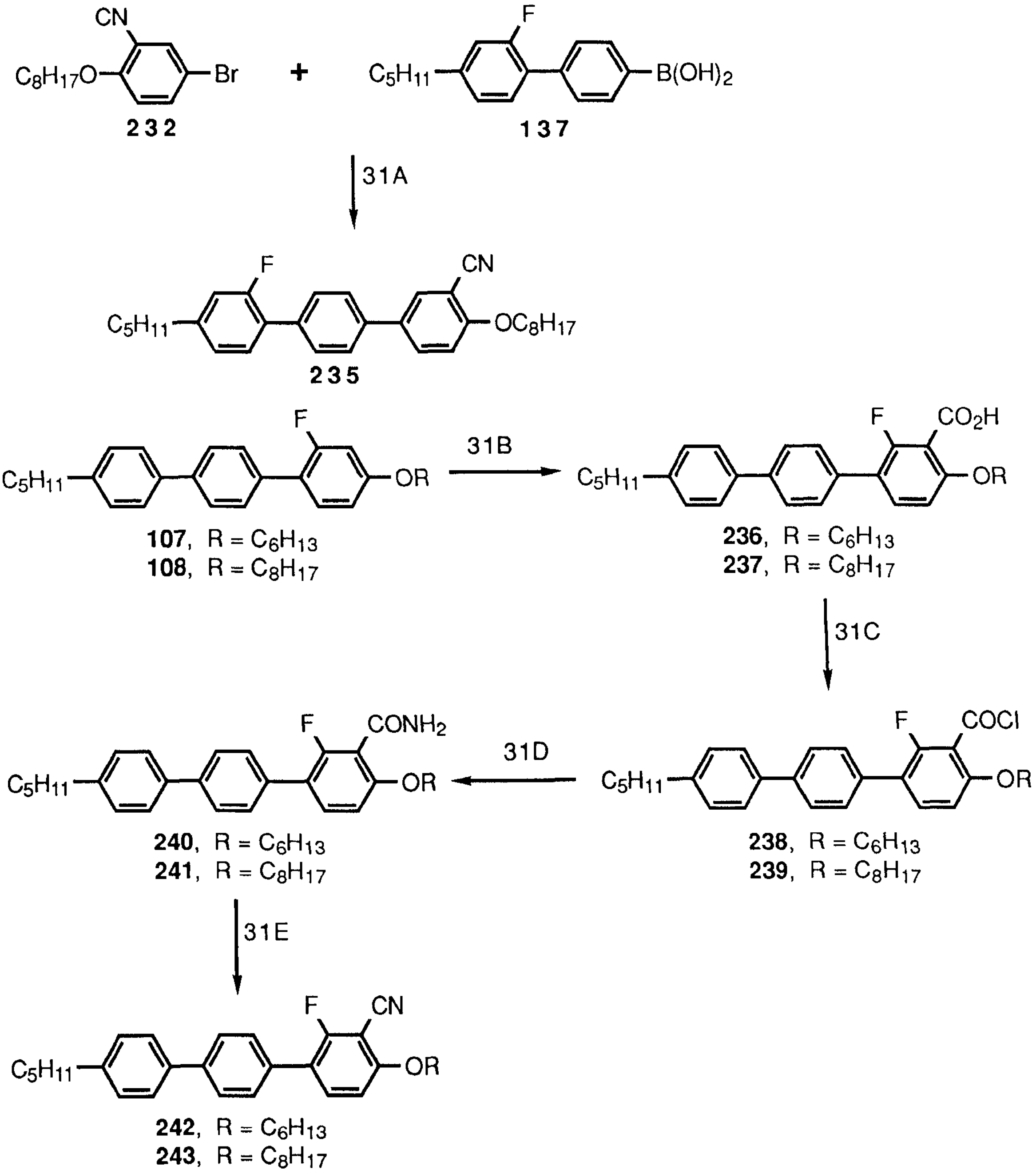


30A ...... RBr, K_2CO_3, acetone.

30B ...... Br_2, $CHCl_3$.

30C ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 31 (p 190-192)



31A ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

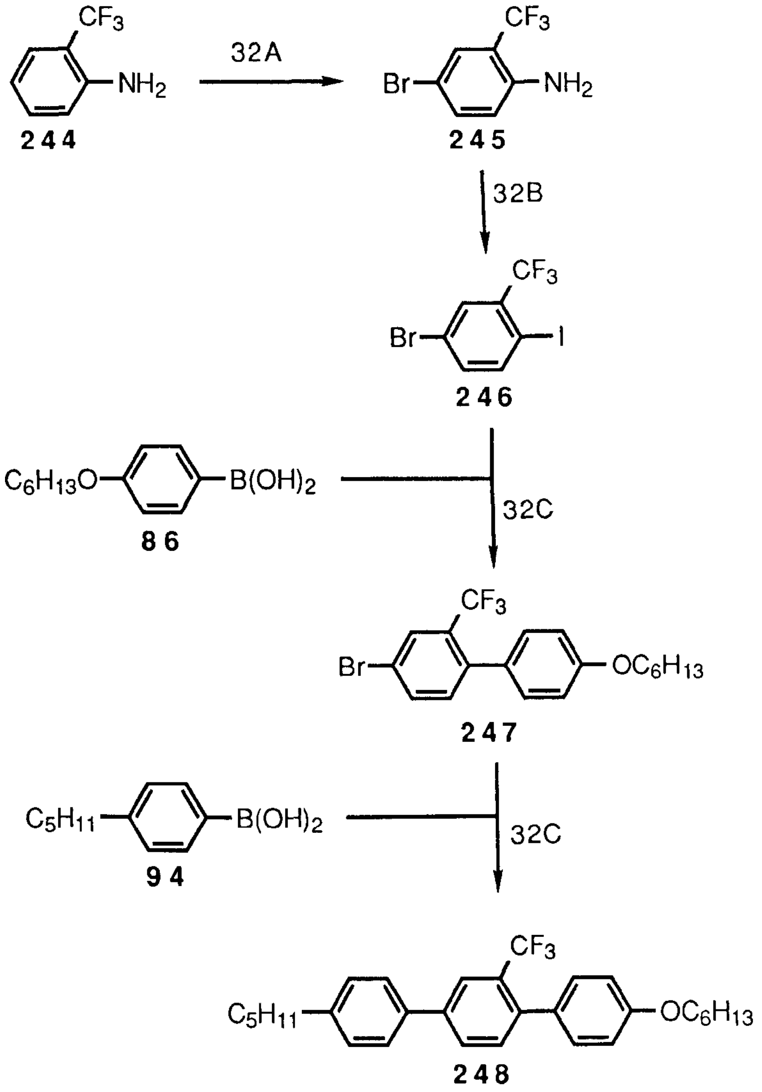
31B ...... (i) nBuLi, THF; (ii) CO_2(solid), Et_2O.

31C ...... Oxalyl chloride, DMF, benzene.

31D ...... 35% Ammonia.

31E ...... Thionyl chloride, DMF.

Scheme 32 (p 192-194)

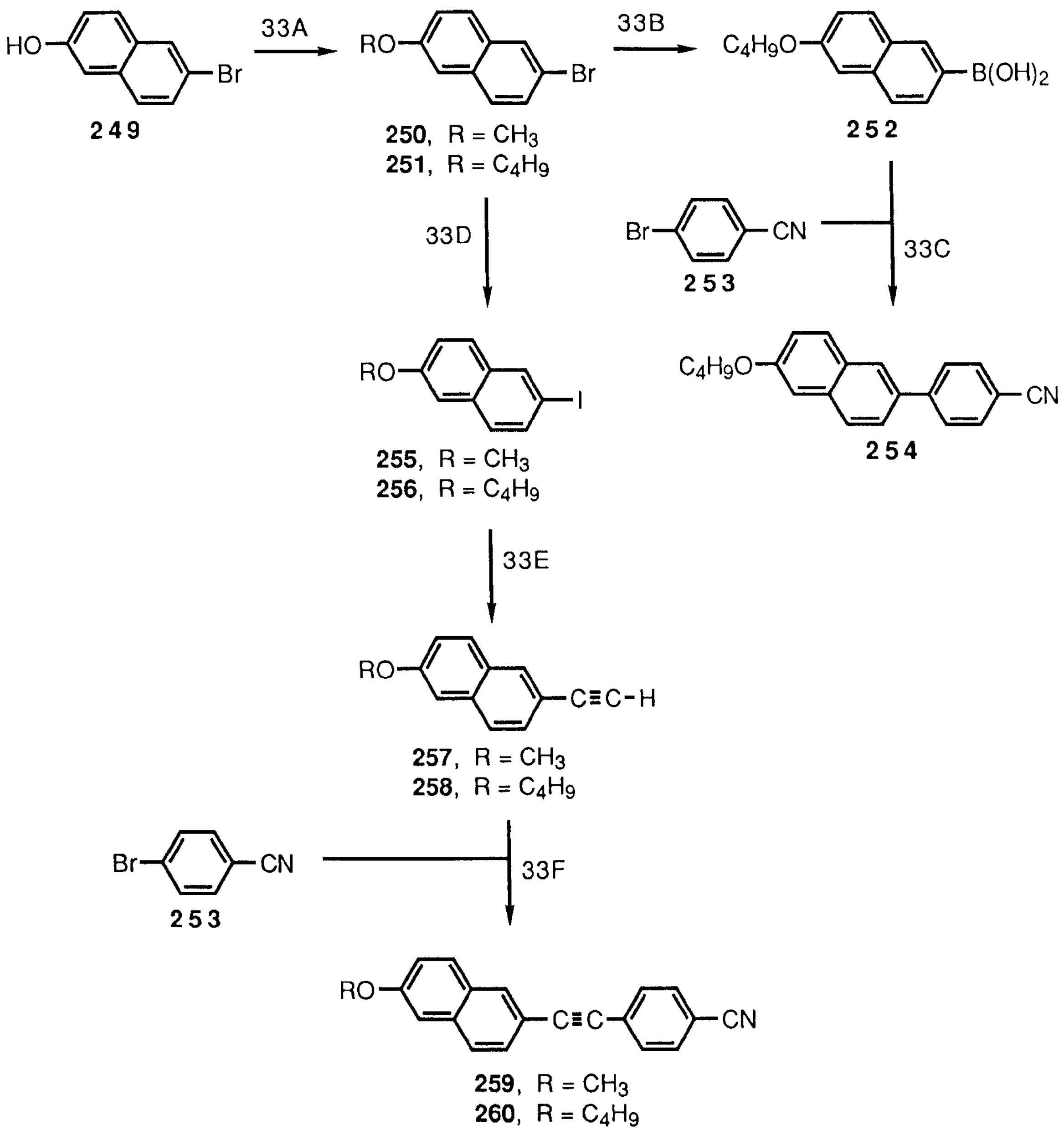


32A ...... NBS, CH_2Cl_2.

32B ...... (i) $NaNO_2$, 36% HCl; (ii) KI.

32C ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

Scheme 33 (p 194-198)



33A ...... Dimethyl sulphate, KOH, water (R = CH_3) or C_4H_9Br, acetone, K_2CO_3.

33B ...... (i) nBuLi, THF; (ii) ($^iPrO)_3B$, THF; (iii) 10% HCl.

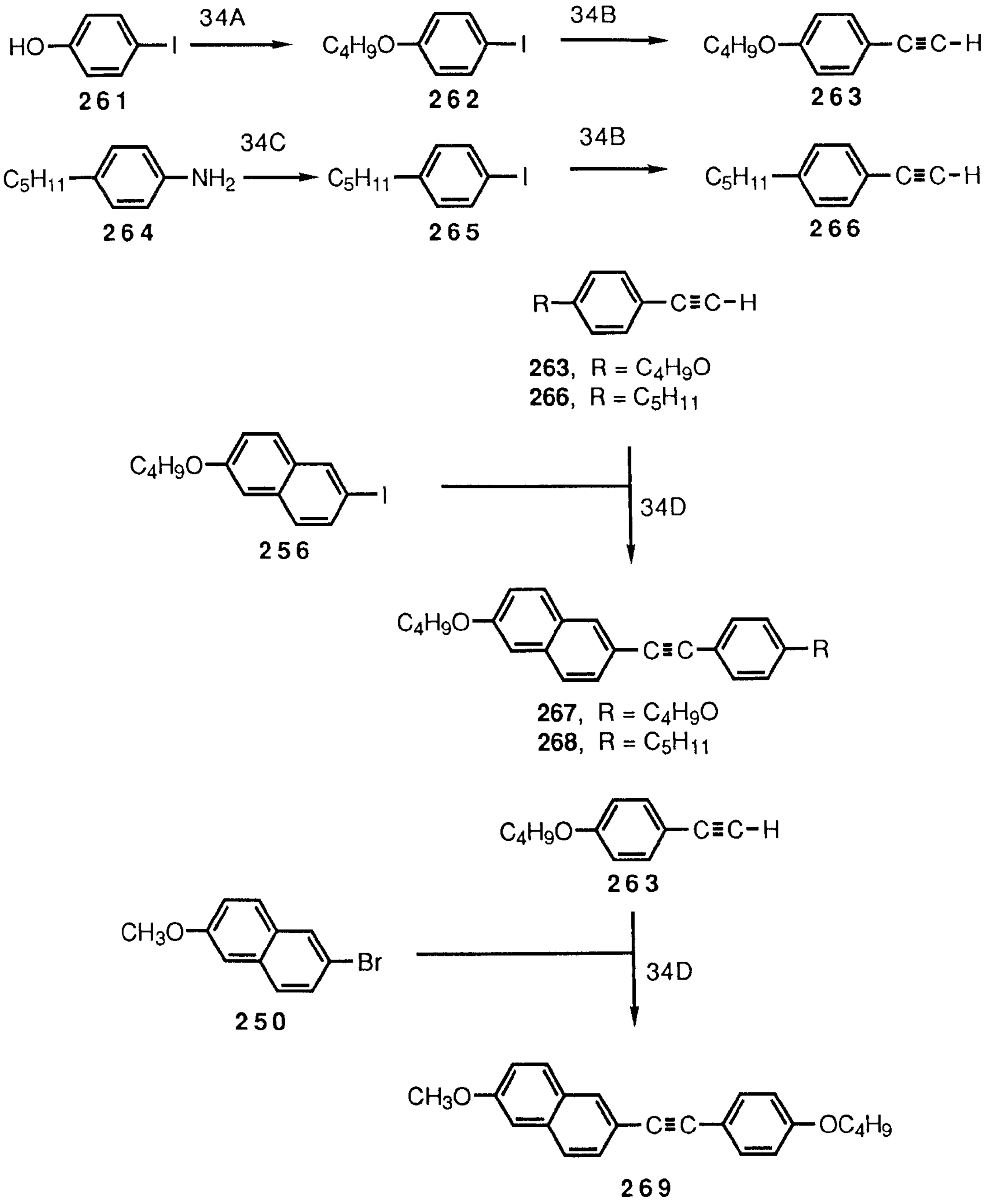
33C ...... $Pd(PPh_3)_4$, benzene, EtOH, 2M-Na_2CO_3.

33D ...... KI, CuI, HMPA.

33E ...... (i) Lithium acetylide ethylenediamine complex, $ZnCl_2$, THF; (ii) $Pd(PPh_3)_4$, THF.

33F ...... (i) nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, THF.

Scheme 34 (p 198-201)



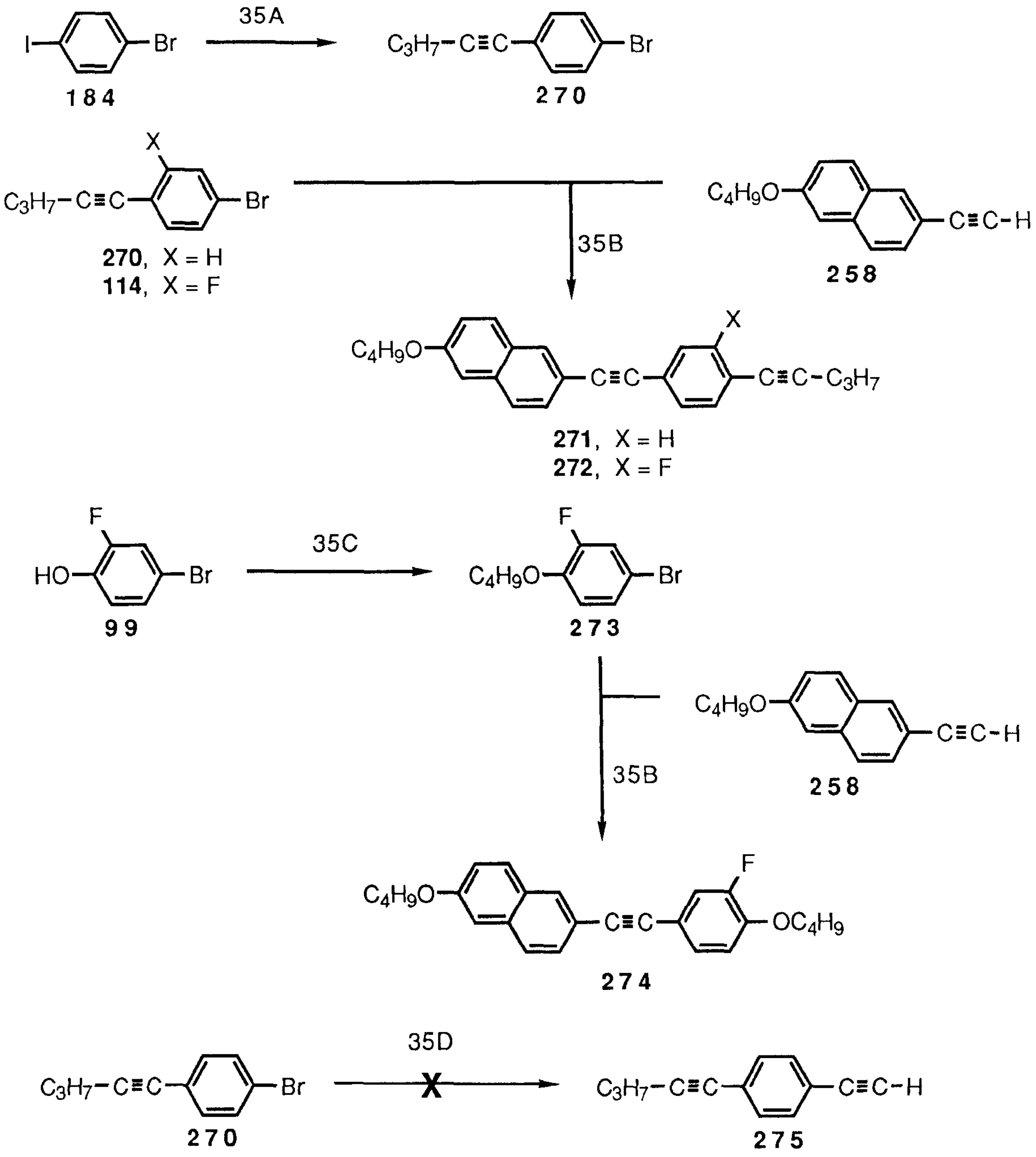
34A ...... C_4H_9Br, acetone, K_2CO_3.

34B ...... (i) Lithium acetylide ethylenediamine complex, $ZnCl_2$, THF; (ii) $Pd(PPh_3)_4$, THF.

34C ...... (i) $NaNO_2$, 36% HCl; (ii) KI.

34D ...... (i) nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, THF.

Scheme 35 (p 202-204)



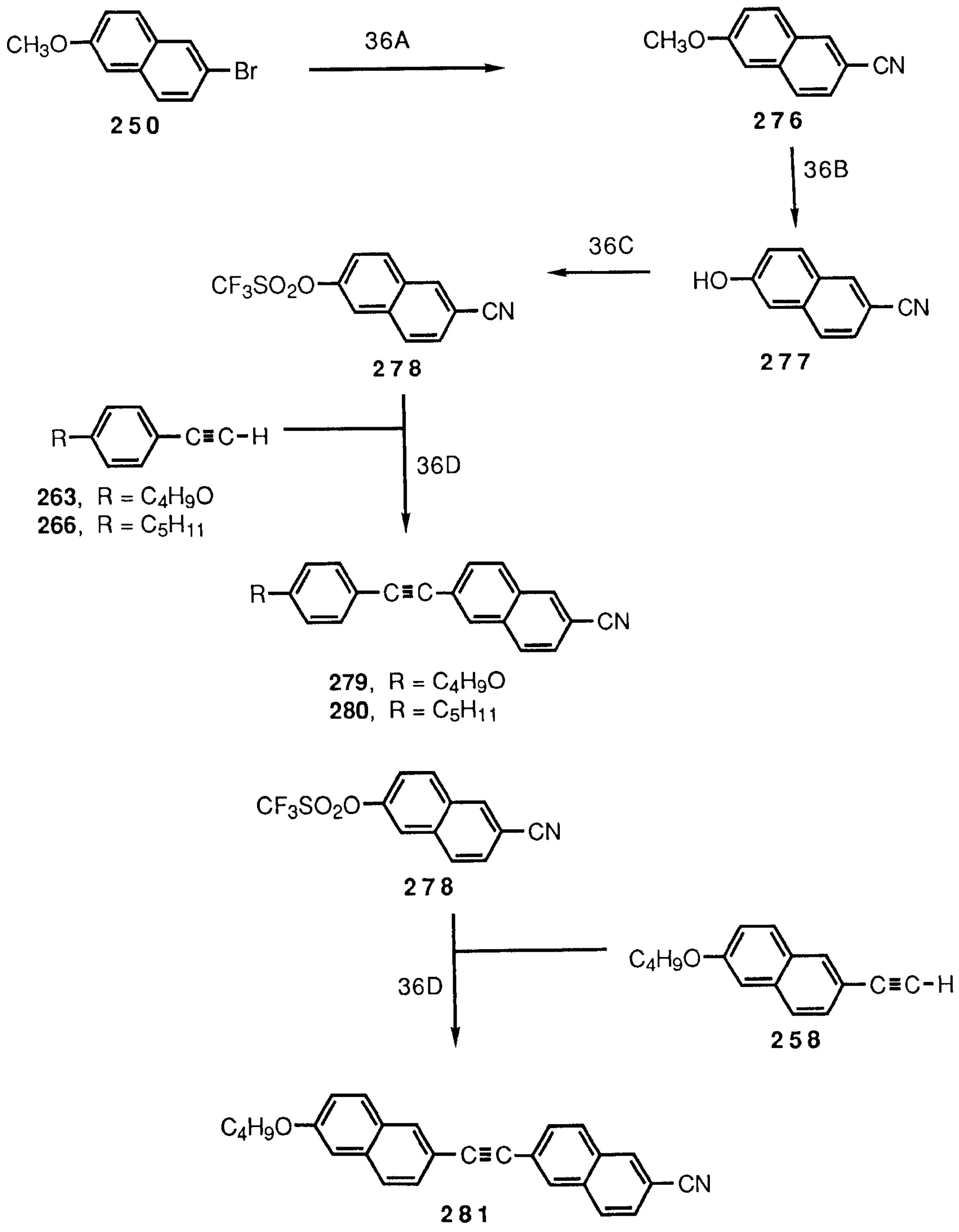
35A ...... (i) Pent-1-yne, nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, THF.

35B ...... (i) nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, THF.

35C ...... C_4H_9Br, butanone, K_2CO_3.

35D ...... (i) Lithium acetylide ethylenediamine complex, $ZnCl_2$, THF; (ii) $Pd(PPh_3)_4$, THF.

Scheme 36 (p 204-207)



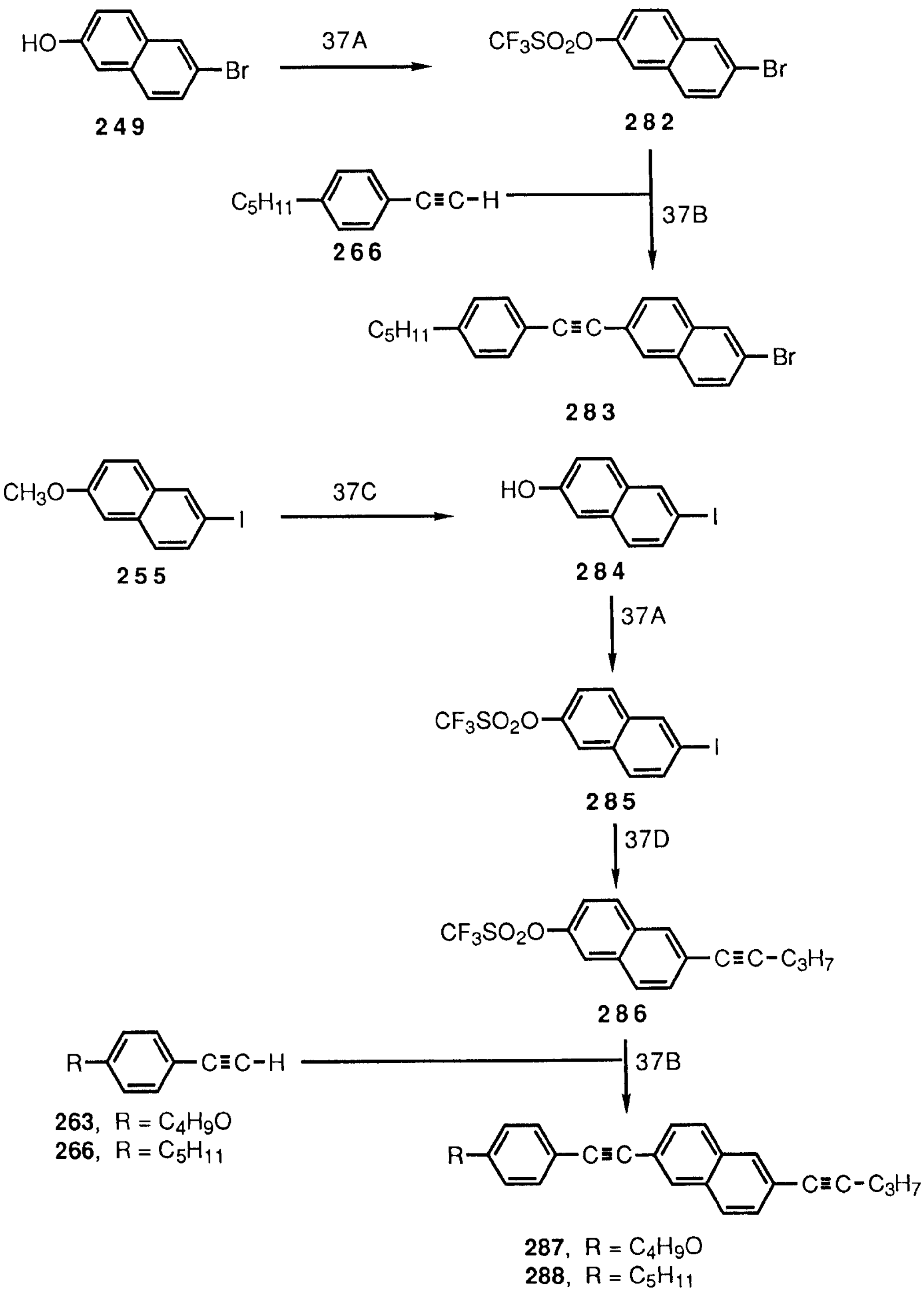
36A ...... CuCN, DMF.

36B ...... BBr_3, CH_2Cl_2.

36C ...... *N*-Phenyltriflamide, Et_3N, CH_2Cl_2.

36D ...... (i) n BuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, LiCl, THF.

Scheme 37 (p 207-210)



37A ...... *N*-Phenyltriflamide, Et_3N, CH_2Cl_2.

37B ...... (i) nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh)_3)_4$, LiCl, THF.

37C ...... BBr_3, CH_2Cl_2.

37D ...... (i) Pent-1-yne, nBuLi, THF; (ii) $ZnCl_2$, THF; (iii) $Pd(PPh_3)_4$, THF.

2.5 Synthetic Methods

4-Methoxyphenylboronic acid (**2**)

A solution of the Grignard reagent, prepared from compound **1** (80.0 g, 0.43 mol) and magnesium (11.96 g, 0.49 mol) in dry THF (300 ml) was added dropwise to a stirred, cooled (-78 °C) solution of tri-isopropyl borate (161.7 g, 0.86 mol) in dry THF (50 ml) under dry nitrogen. The stirred mixture was allowed to warm to room temperature overnight and was then stirred at room temperature for 1 h with 10% hydrochloric acid (300 ml). The product was extracted into ether (twice), the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a cream-coloured solid (58.5 g) which was recrystallised from water to yield colourless crystals.

Yield 27.7 g (43%); mp 201-202 °C (lit.,[175] 202-204 °C); ^1H nmr ($CDCl_3$) δ 3.90(3H, s), 5.50(2H, s), 6.85(2H, d), 7.80(2H, d); ir (KCl) ν_{max} 3600-3100, 2990, 2870, 1610, 1360, 1250, 1170, 1110, 1020, 1010 cm^{-1}; ms *m/z* 152(M^+), 134.

A cream-coloured oil was separated during the above recrystallisation which solidified on cooling to give a cream coloured solid (the trimeric boronic acid anhydride).

Yield 17.5 g ^1H nmr ($CDCl_3$) δ 3.70(3H, s), 6.95(2H, d), 8.10(2H, d); ir (KCl) ν_{max} 2990, 2870, 1610, 1360, 1250, 1170, 1110, 1020, 1010; ms *m/z* 402(M^+), 201, 134.

4-Bromo-2-fluoroaniline (**5**)

N-Bromosuccinimide (160.4 g, 0.90 mol) was added in small portions to a stirred, cooled (-10 to 0 °C) solution of compound **3** (100.0 g, 0.90 mol) in dry dichloromethane (400 ml). The mixture was stirred at 0 °C for 45 min (glc analysis revealed a complete reaction), washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a red solid which was steam distilled to yield a colourless solid.

Yield 120.0 g (70%); mp 41-42 °C; ^1H nmr ($CDCl_3$) δ 3.70(2H, s), 6.65(1H, q), 7.04(1H, oct), 7.14(1H, q); ir (KCl) ν_{max} 3410, 3320, 1630, 1580, 1500, 1210

cm^{-1}; ms *m*/*z* 191(M^+), 189(M^+), 110, 94.

4-Bromo-2,6-difluoroaniline (**6**)

A solution of bromine (130.0 g, 0.81 mol) in glacial acetic acid (200 ml) was added slowly, dropwise to a stirred solution of compound **4** (101.5 g, 0.79 mol) in glacial acetic acid (500 ml) at ~0 °C. The mixture was stirred at room temperature for 2 h (glc analysis revealed a complete reaction); sodium thiosulphate (50 g), sodium acetate (125 g) and water were added and the mixture was cooled in a refrigerator overnight. The product was filtered off, extracted into ether, the ether extract was washed with water, 5% sodium hydroxide, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a pale yellow solid which was steam distilled to yield a colourless solid.

Yield 117.9 g (72%); mp 67-68 °C; ^1H nmr ($CDCl_3$) δ 3.65(2H, s), 7.20(2H, d); ir (KCl) ν_{max} 3420, 3330, 1640, 1610, 1580, 1500, 1430 cm^{-1}; ms *m*/*z* 209(M^+), 207(M^+), 128, 108, 101.

4-Bromo-2-fluorobenzonitrile (**7**)

Concentrated sulphuric acid (60 ml) was added dropwise to a stirred mixture of compound **5** (75.0 g, 0.39 mol), water (150 ml) and glacial acetic acid (185 ml). The clear solution was cooled to -5 °C (a suspension formed) and a solution of sodium nitrite (30.0 g, 0.44 mol) in water (100 ml) was added dropwise; the stirred mixture was maintained at -5 °C for 15 min.

A solution of potassium cyanide (128.3 g, 1.98 mol) in water (300 ml) was added dropwise to a stirred solution of copper(II) sulphate pentahydrate (118.1 g, 0.48 mol) in water (300 ml) and ice (300 g) at 10 to 20 °C. Sodium hydrogen carbonate (265.1 g, 3.16 mol) and cyclohexane (450 ml) were added, the temperature was raised to 50 °C and the cold diazonium salt mixture was added in portions with rapid stirring. The mixture was cooled, the organic layer was separated and the aqueous layer was washed with ether (twice). The combined organic extracts were washed with water, 10% sodium hydroxide, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to afford a dark brown solid which was steam distilled to yield an off-white solid.

Yield 59.2 g (76%); mp 69-70 °C; ^{1}H nmr ($CDCl_3$) δ 7.44(1H, d), 7.47(1H, d), 7.52(1H, q); ir (KCl) ν_{max} 2240, 1600, 1570, 1480, 1400, 1230, 1060, 890, 860, 820 cm^{-1}; ms *m/z* 201(M$^+$), 199(M$^+$), 120, 100.

4-Bromo-2,6-difluorobenzonitrile (**8**)

A stirred mixture of compound **6** (56.0 g, 0.27 mol) and concentrated sulphuric acid-water (1:1, 250 ml) was heated until a solution was obtained. The mixture was cooled to -10 °C and a solution of sodium nitrite (30.9 g, 0.45 mol) in water (70 ml) was added dropwise. The mixture was stirred at -5 °C for 2.5 h.

A solution of potassium cyanide (97.5 g, 1.50 mol) in water was added dropwise to a stirred solution of copper(II) sulphate pentahydrate (86.5 g, 0.35 mol) in water (200 ml) and ice (130 g). Sodium hydrogen carbonate (300 g), cyclohexane (1200 ml) and glacial acetic acid (130 ml) were added, the temperature was raised to 50 °C and the cold diazonium salt mixture was added in portions with rapid stirring. The mixture was cooled, the organic layer was separated and the aqueous layer was washed with ether (twice). The combined organic extracts were washed with water, 10% sodium hydroxide, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to afford a dark brown solid which was steam distilled to yield a light-orange solid.

Yield 31.7 g (54%); mp 79-80 °C; ^{1}H nmr ($CDCl_3$) δ 7.30(d); ir (KCl) ν_{max} 3050, 2250, 1610, 1560, 1480, 1430, 1200, 1040 cm^{-1}; ms *m/z* 219(M$^+$), 217(M$^+$), 138, 87.

4-Cyano-3-fluoro-4'-methoxybiphenyl (**9**)

A solution of compound **2** (10.64 g, 0.070 mol) in ethanol (90 ml) was added dropwise to a stirred mixture of compound **7** (12.00 g, 0.060 mol) and tetrakis(triphenylphosphine)palladium(0) (2.10 g, 1.82 mmol) in benzene (125 ml) and 2M-sodium carbonate (100 ml) at room temperature under dry nitrogen. The stirred mixture was heated under reflux (95 °C) for 4.5 h (*i.e.*, until glc analysis revealed a complete reaction). The mixture was cooled and stirred for 1 h at room temperature with 30% hydrogen peroxide (2 ml). The mixture was further cooled to 2 °C, and the product was filtered off and washed with water. The product was dried ($CaCl_2$) *in vacuo* to yield a yellow powder.

Yield 11.90 g (88%); mp 153-154 °C; ^1H nmr ($CDCl_3$) δ 3.90(3H, s), 7.00(2H, d), 7.38(1H, q), 7.44(1H, q), 7.55(2H, d), 7.65(1H, q); ir (KCl) ν_{max} 2220, 1610, 1490, 1250, 1170, 820 cm^{-1}; ms *m/z* 227(M^+), 212, 195, 184, 158.

4-Cyano-3,5-difluoro-4'-methoxybiphenyl **(10)**

Quantities: compound **2** (11.50 g, 0.076 mol), compound **8** (15.00 g, 0.069 mol), tetrakis(triphenylphosphine)palladium(0) (2.38 g, 2.06 mmol).

The experimental procedure was as described for the preparation of compound **9**.

Yield 14.10 g (84%); mp 206-207 °C; ^1H nmr ($CDCl_3$) δ 3.90(3H, s), 7.00(2H, d), 7.20(2H, d), 7.50(2H, d); ir (KCl) ν_{max} 2800, 2240, 1630, 1600, 1560, 1490, 1440, 1410, 1290, 1230 cm^{-1}; ms *m/z* 245(M^+), 230, 213, 202.

4-Cyano-3-fluoro-4'-hydroxybiphenyl **(11)**

A solution of boron tribromide (12.0 ml, 31.8 g, 0.13 mol) in dry dichloromethane (100 ml) was added dropwise to a stirred, cooled (-78 °C) solution of compound **9** (14.00 g, 0.062 mol) in dry dichloromethane (250 ml) under dry nitrogen. The stirred mixture was allowed to warm to room temperature overnight (glc analysis revealed a complete reaction). Water was carefully added and a yellow precipitate was produced. The product was extracted into ether (twice), and the combined organic extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a pale-yellow powder.

Yield 13.10 g (100%); mp 201-202 °C; ^1H nmr ($CDCl_3$) δ 6.95(2H, d), 7.40(2H, 2xq), 7.45(2H, d), 7.65(1H, q), 9.45(1H, s); ir (KCl) ν_{max} 3400-2900, 2240, 1630, 1610, 1560, 1490, 1450, 1410, 1370, 1270, 1180, 820 cm^{-1}; ms *m/z* 213(M^+), 184, 164, 158.

4-Cyano-3,5-difluoro-4'-hydroxybiphenyl (**12**)

Quantities: compound **10** (12.22 g, 0.050 mol), boron tribromide (25.0 ml, 61.5 g, 0.25 mol).

The experimental procedure was as described for the preparation of compound **11**.

Yield 13.30 g (100%); mp 230-231 °C; ^{1}H nmr ($CDCl_3$) δ 6.60 (2H, d), 6.95(2H, d), 7.13(2H, d), 9.20(1H, s); ir (KCl) ν_{max} 3390, 2250, 1630, 1610, 1590, 1490, 1460, 1420, 1280, 1230 cm^{-1}; ms *m/z* 231(M^+), 211, 202.

2,6-Difluoro-4-methoxybenzoic acid (**14**)

A solution of n-butyllithium (25.0 ml, 10.0M in hexane, 0.25 mol) was added dropwise to a stirred, cooled (-78 °C) solution of compound **13** (35.9 g, 0.25 mol) in dry THF (200 ml) under dry nitrogen. The stirred mixture was maintained under these conditions for 2.5 h and then poured into a slurry of solid carbon dioxide and dry ether. The product was extracted into 10% sodium hydroxide (twice), the combined basic extracts were acidified with 36% hydrochloric acid. The product was extracted into ether (twice), the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a colourless solid.

Yield 46.5 g (99%); mp 184-185 °C; ^{1}H nmr ($CDCl_3$) δ 3.85(3H, s), 6.50(2H, d), 11.00(1H, s); ir (KCl) ν_{max} 3200-2500, 2680, 2550, 1700, 1630, 1570, 1450, 1420, 1360, 1330, 1290, 1160, 1050, 850 cm^{-1}; ms *m/z* 188(M^+), 171, 141, 126, 97.

2,6-Difluoro-4-methoxybenzoyl chloride (**15**)

A solution of oxalyl chloride (36.5 g, 0.29 mol) in dry benzene (50 ml) was added dropwise to a stirred solution of compound **14** (25.50 g, 0.136 mol) and dry DMF (40 drops) in dry benzene (500 ml) at room temperature. The mixture was stirred at room temperature overnight and the excess of oxalyl chloride and benzene were removed *in vacuo*.

2,6-Difluoro-4-methoxybenzamide **(16)**

The crude acid chloride **(15)** was dissolved in dry diglyme (60 ml) and added dropwise to gently stirred 35% ammonia (750 ml) at room temperature. The resulting precipitate was filtered off and dried ($CaCl_2$) *in vacuo* to give a colourless solid.

Yield 21.20 g (81%); mp 158-159 °C; ^1H nmr ($CDCl_3$) δ 3.85(3H, s), 6.50(2H, d), 7.25(2H, d); ir (KCl) ν_{max} 3400, 3200, 1640, 1580, 1440, 1400, 1350, 1200, 1160, 1140, 1050, 1030, 830 cm^{-1}; ms *m/z* 187(M^+), 171, 149, 121, 118.

2,6-Difluoro-4-methoxybenzonitrile **(17)**

A solution of thionyl chloride (139.0 g, 1.17 mol) in dry DMF (150 ml) was added to a stirred solution of compound **16** (20.00 g, 0.107 mol) in dry DMF (250 ml) at room temperature. The mixture was stirred at room temperature overnight and then poured onto ice-water. The product was extracted into ether (twice), and the combined ethereal extracts were washed with water, aqueous sodium hydrogen carbonate, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give off-white crystals.

Yield 17.70 g (95%); mp 59-60 °C; ^1H nmr ($CDCl_3$) δ 3.90(3H, s), 6.55(2H, d); ir (KCl) ν_{max} 3090, 2250, 1640, 1580, 1500, 1440, 1370, 1210, 1200, 1040, 960 cm^{-1}; ms *m/z* 169(M^+), 139, 132, 126, 120.

2,6-Difluoro-4-hydroxybenzonitrile **(18)**

A stirred, homogeneous mixture of finely powdered, compound **17** (17.0 0g, 0.101 mol), aluminium chloride (29.40 g, 0.220 mol) and sodium chloride (7.10 g, 0.121 mol) was heated to 180 °C over 25 min and then at 180 °C for 1.25 h (glc and tlc analysis both revealed a complete reaction). Ice-water was added, and the product was extracted into ether (twice). The combined ethereal extracts were washed with water, and the product was extracted into 10% sodium hydroxide (twice) and the combined basic extracts were acidified with 36% hydrochloric acid. The product was extracted into ether (twice) and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a fawn-coloured solid.

Yield 14.60 g (94%); mp 119-120 °C; ^{1}H nmr ($CDCl_3$) δ 6.50 (2H, d), 10.90(1H, s); ir (KCl) ν_{max} 3300, 2250, 1640, 1600, 1510, 1480, 1270, 1160, 1040, 850 cm^{-1}; ms *m/z* 155(M$^+$), 127, 107, 100.

4-Butoxybenzoic acid (**20**)

1-Bromobutane (22.60 g, 0.165 mol) was added dropwise at room temperature to a stirred mixture of compound **19** (15.00 g, 0.109 mol) in ethanol (60 ml) and sodium hydroxide (10.60 g) in the minimum amount of water. The stirred mixture was heated under reflux overnight (tlc analysis revealed a complete reaction), and then the ethanol was removed *in vacuo* and an equal volume of water was added. The mixture was boiled to give a solution, cooled, washed with ether and the separated basic layer was acidified with 36% hydrochloric acid. The cooled product was filtered off, washed with water and dried ($CaCl_2$) *in vacuo* to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 12.10 g (57%); transitions (°C) K 147.0 N 160.0 I; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.80(2H, d), 8.00(2H, d); ir (KCl) ν_{max} 3300-2500, 2980, 2890, 2670, 2550, 1680, 1610, 1590, 1520, 1300, 1260, 1170 cm^{-1}; ms *m/z* 194(M$^+$), 138, 121, 65.

2-Fluoro-4-pent-1'-ynylbenzonitrile (**21**)

A solution of n-butyllithium (10.0 ml, 10.0M in hexane, 0.10 mol) was added dropwise to a stirred, cooled (-5 to 0 °C) solution of pent-1-yne (6.80 g, 0.100 mol) in dry THF (50 ml) under dry nitrogen. This mixture was stirred for 10 min and then a solution of dry zinc chloride (13.63 g, 0.100 mol) in dry THF (100 ml) was added dropwise at -5 to 0 °C. The mixture was stirred at room temperature for 15 min and a solution of compound **7** (20.00 g, 0.100 mol) in dry THF (100 ml) was added dropwise at -5 to 0 °C followed by the addition of tetrakis(triphenylphosphine)palladium(0) (2.31 g, 2.0 mmol). The mixture was stirred at room temperature overnight (glc analysis revealed a complete reaction) and poured into 10% hydrochloric acid. The product was extracted into ether (twice), and the combined ethereal extracts were washed with aqueous sodium hydrogen carbonate and dried ($MgSO_4$). The solvent was removed *in vacuo* to afford an orange liquid which was filtered through a short alumina column eluted with dichloromethane, the solvent was removed *in vacuo* and the residue was distilled to yield a pale-yellow oil.

Yield 17.60 g (94%); bp 100-105 °C at 0.1 mmHg; ^1H nmr ($CDCl_3$) δ 1.05(3H, t), 1.65(2H, sext), 2.40(2H, t), 7.18(1H, q), 7.24(1H, q), 7.50(1H, q); ir (KCl) ν_{max} 2980, 2950, 2880, 2240, 1620, 1550, 1500, 1420, 1180, 1120 cm^{-1}; ms *m/z* 187(M^+), 172, 158, 152, 145, 131.

Attempted Preparation of 2-Fluoro-4-pent-1'-ynylbenzoic acid (**22**)

A mixture of concentrated sulphuric acid (165 ml) and water (165 ml) was added dropwise to a stirred solution of compound **21** (14.00 g, 0.075 mol) in glacial acetic acid (330 ml) at room temperature. The stirred mixture was heated under reflux for 72 h, cooled and the product was extracted into ether (twice). The combined ethereal extracts were washed with water and the product was extracted into 10% sodium hydroxide (twice). The combined basic extracts were acidified with 36% hydrochloric acid and the product was extracted into ether (twice). The combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give an off-white solid (2-fluoro-4-pentanoylbenzoic acid).

Yield 5.62 g (33%); mp 114-115 °C; ^1H nmr ($CDCl_3$) δ 0.95(3H, t), 1.45(2H, sext), 1.65(2H, quint), 3.00(2H, sext), 7.75(2H, q), 8.10(1H, t); ir (KCl) ν_{max} 2960, 2940, 2880, 2660, 1700, 1690, 1620, 1570, 1430, 1410, 1290, 1240, 1170, 1080 cm^{-1}; ms *m/z* 224(M^+), 182, 167, 154.

2-Fluoro-4-pentylbenzonitrile (**23**)

A stirred mixture of compound **21** (16.00 g, 0.085 mol) and 5% palladium-on-charcoal (4.00 g) in ethanol (100 ml) was hydrogenated at room temperature and atmospheric pressure for 8 h (glc analysis revealed a complete reaction). The catalyst was filtered off and the solvent was removed *in vacuo* to yield a pale-orange solid.

Yield 15.35 g (95%); mp 20 °C; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.65(2H, t), 7.10(2H, m), 7.60(1H, q); ir (KCl) ν_{max} 2960, 2880, 2250, 1640, 1570, 1510; ms *m/z* 191(M^+), 134.

2-Fluoro-4-pentylbenzoic acid **(24)**

A mixture of concentrated sulphuric acid (150 ml) and water (150 ml) was added dropwise to a stirred solution of compound **23** (15.00 g, 0.078 mol) in glacial acetic acid (300 ml). The stirred mixture was heated under reflux for 48 h, cooled in a refrigerator overnight and the product was filtered off. The product was dissolved in ether, extracted into 10% sodium hydroxide (twice). The combined basic extracts were acidified with 36% hydrochloric acid and the product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a brown crystalline solid.

Yield 11.50 g (70%); transitions (°C) K 85.0 N 91.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.65(2H, t), 6.96(1H, q), 7.05(1H, q), 7.94(1H, t); ir (KCl) ν_{max} 3300-2500, 1695, 1670, 1630, 1570, 1500, 1450, 1300, 1210, 1160 cm^{-1}; ms *m/z* 210(M^+), 193, 175, 167, 154.

4-Butoxy-2-fluorobenzonitrile **(26)**

A solution of 1-bromobutane (18.00 g, 0.130 mol) in acetone (30 ml) was added dropwise to stirred refluxing mixture of compound **25** (15.00 g, 0.109 mol) and potassium carbonate (46.0 g, 0.33 mol) in acetone (300 ml). The stirred mixture was heated under reflux for 24 h (*i.e.*, until glc analysis revealed a complete reaction). The potassium carbonate was filtered off, water was added to the filtrate and the product was extracted into ether (twice). The combined ethereal extracts were washed with water, 5% sodium hydroxide, water and dried ($MgSO_4$). The solvent and the excess of 1-bromobutane were removed *in vacuo* to yield a pale orange solid.

Yield 19.50 g (93%); mp 25-26 °C; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.80(1H, q), 7.00(1H, q), 7.80(1H, q); ir (KCl) ν_{max} 2960, 2880, 2250, 1640, 1570, 1510, 1460, 1440, 1340, 1300, 1250 cm^{-1}; ms *m/z* 193(M$^+$), 188, 149, 120.

4-Butoxy-2-fluorobenzoic acid (**27**)

Quantities: compound **26** (19.00 g, 0.098 mol).

The experimental procedure was as described for the preparation of compound **24**. Yield (pale-yellow crystals) 18.70 g (90%); transitions (°C) K 108.0 N 125.0 I; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.65(1H, q), 6.75(1H, q), 7.97(1H, t); ir (KCl) ν_{max} 3300-2500, 2960, 2880, 1680, 1620, 1575, 1455, 1420, 1400, 1340, 1275, 1245, 1180, 1150, 1040 cm^{-1}; ms *m/z* 212(M$^+$), 188, 179, 168, 156, 139.

Pentyl tosylate (**28**)

Toluene-4-sulphonyl chloride (19.50 g, 0.010 mol) was added in small portions to a stirred, cooled (0 °C) solution of pentan-1-ol (6.10 g, 0.069 mol) in chloroform (60 ml) and pyridine (10 ml). The mixture was stirred for 2.5 h at room temperature (tlc analysis revealed a complete reaction). Ether and water were added, the organic layer was washed successively with water, 10% hydrochloric acid, water, aqueous sodium hydrogen carbonate, water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - ether, 49:1] to yield a colourless liquid.

Yield 14.20 g (85%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.50(3H, s), 4.00(2H, t), 7.40(2H, d), 7.85(2H, d); ir (film) ν_{max} 2970, 2950, 2880, 1600, 1500, 1475, 1360, 1180, 1100 cm^{-1}; ms *m/z* 242(M$^+$), 190, 173, 155, 107.

Attempted Preparation of 1,3-Difluoro-5-pentylbenzene (**32**)

Method A

A solution of compound **28** (0.9879 g, 4.08 mmol) was added dropwise to a stirred, cooled (-15 °C) mixture of the Grignard reagent, prepared from compound **29** (1.0129 g, 5.25 mmol) and magnesium (0.1414 g, 5.82 mmol) in dry ether (5 ml), and a portion of a catalyst solution (2 ml), prepared from lithium chloride (0.2202 g, 5.00 mmol), and copper(II) chloride (0.3403 g, 2.5 mmol) in dry THF (25 ml). The stirred mixture was allowed to warm to room temperature and was stirred at room temperature for 20 h (glc analysis revealed an absence of the desired product). This procedure was repeated at -78 °C with the same result.

Method B

A solution of the Grignard reagent, prepared from 1-bromopentane (1.0105 g, 6.69 mmol) and magnesium (0.1778 g, 7.32 mmol) in dry ether (5 ml) was added dropwise to a stirred, refluxing mixture of compound **29** (1.0782 g, 5.59 mmol) and Ni(dppp)Cl_2 (0.1908, 0.35 mmol) in dry ether (5 ml) (glc analysis revealed an absence of the desired product).

Method C

Copper(I) chloride (0.1012 g, 1.01 mmol) was added to a solution of the Grignard reagent prepared from compound **29** (1.2355 g, 6.40 mmol) and magnesium (0.1670 g, 6.87 mmol) in dry THF (5 ml) followed by dropwise addition of a solution of 1-bromopentane (1.1463 g, 7.60 mmol) in dry THF (4 ml). The stirred mixture was heated under reflux for 1.5 h (glc analysis revealed a presence of the desired product), cooled and poured into 20% hydrochloric acid (45 ml). The mixture was washed with dichloromethane, and the organic layer was washed with water and dried ($MgSO_4$). The residual mixture was distilled at atmospheric pressure but isolation of the desired product proved impossible.

Method D

Copper(I) chloride (0.1000 g, 1.01 mmol) was added to the solution of the Grignard reagent prepared from compound **29** (2.0125 g, 0.010 mol) and magnesium

(0.2484 g, 0.010 mol) in dry THF (5 ml) followed by dropwise addition of a solution of compound **28** (4.7741 g, 0.020 mol) in dry THF (3 ml). The stirred mixture was heated under reflux for 6 h (glc analysis revealed a presence of the desired product), cooled and poured onto 36% hydrochloric acid (25 ml) and ice (200 g). The mixture was washed with dichloromethane, and the organic layer was washed with water and dried ($MgSO_4$). The residual mixture was distilled at atmospheric pressure but isolation of the desired product proved impossible.

1-(3,5-Difluorophenyl)pentan-1-ol (**30**)

A solution of pentanal (19.00 g, 0.221 mol) in dry ether (75 ml) was added dropwise to a stirred solution of the Grignard reagent at room temperature, under dry nitrogen, prepared from compound **29** (50.2 g, 0.26 mol) and magnesium (7.25 g, 0.300 mol) in dry THF (100 ml). The stirred mixture was heated under reflux for 2 h, cooled and aqueous ammonium chloride (300 ml) was added. The product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a pale-orange liquid which was distilled to yield a colourless liquid. [Smaller quantities of crude product were purified by column chromatography (silica gel / dichloromethane) to yield a colourless liquid (92%)].

Yield 35.8 g (69%); bp 90 °C at 0.5 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.75(3H, t), 1.25(4H, m), 2.10(1H, s), 3.65(2H, q), 4.70(1H, t), 6.80-7.10(3H, m); ir (film) ν_{max} 3500-3100, 2960, 2940, 2860, 1630, 1600, 1485, 1275, 1205, 830 cm^{-1}; ms *m*/*z* 200(M^+), 151, 143, 127.

1,3-Difluoro-5-pent-1-enylbenzene (**31**)

Phosphorus(V) oxide (64.5 g, 0.45 mol) was added in portions to a stirred solution of compound **30** (35.0 g, 0.175 mol) in dry pentane (150 ml) at room temperature. The mixture was stirred at room temperature overnight (glc analysis revealed a complete reaction) and filtered.

1,3-Difluoro-5-pentylbenzene **(32)**

5% Palladium-on-charcoal (4.0 g) was added to the above filtrate [*i.e.*, compound **31** in pentane (150 ml)] at room temperature. The stirred mixture was hydrogenated at room temperature and atmospheric pressure for 4 h (*i.e.*, until glc analysis revealed a complete reaction) and the mixture was filtered. The majority of the pentane was removed *in vacuo* and the final traces of pentane were distilled off (760 mmHg) at 38 °C and the residue was then distilled to yield a colourless liquid.

Yield 23.40 g (73%); bp 200 °C at 760 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.60(2H, t), 6.60(3H, m); ir (film) ν_{max} 2980, 2930, 2870, 1630, 1600, 1640, 1330, 1140, 1120 cm^{-1}; ms *m/z* 184(M^+), 168, 141.

2,6-Difluoro-4-pentylbenzoic acid **(33)**

A solution of n-butyllithium (2.70 ml, 10.5M in hexane, 0.028 mol) was added dropwise to a stirrred, cooled (-78 °C) solution of compound **32** (5.10 g, 0.028 mol) in dry THF (30 ml) under dry nitrogen. The stirred mixture was maintained under these conditions for 2.5 h and then poured onto a slurry of solid carbon dioxide and dry ether. The product was extracted into 10% sodium hydroxide and the separated ether layer was washed with 10% sodium hydroxide, and the combined basic extracts were acidified with 36% hydrochloric acid. The product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a colourless solid.

Yield 5.80 g (91%); mp 75-76 °C; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.60(2H, quint), 2.65(2H, t), 6.80(2H, d), 7.30(1H, s); ir (KCl) ν_{max} 3300-2500, 2680, 2550, 1690, 1640, 1570, 1490, 1440, 1410, 1285, 1210 cm^{-1}; ms *m/z* 228(M^+), 186, 172, 155.

1-Butoxy-3,5-difluorobenzene **(35)**

Quantities: compound **34** (9.10 g, 0.070 mol), 1-bromobutane (11.00 g, 0.080

mol), potassium carbonate (30.0 g, 0.22 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 11.70 g (90%); bp 204 °C at 760 mmHg; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.75(2H, quint), 3.95(2H, t), 6.40(3H, m); ir (film) ν_{max} 2980, 2880, 1630, 1470, 1350, 1130 cm^{-1}; ms *m/z* 186(M$^+$), 138, 130, 112, 100.

4-Butoxy-2,6-difluorobenzoic acid **(36)**

Quantities: compound **35** (7.00 g, 0.038 mol), n-butyllithium (3.60 ml, 10.5M in hexane, 0.038 mol).

The experimental procedure was as described for the preparation of compound **33**.

Yield 8.30 g (96%); mp 110-112 °C; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.50(2H, d), 7.30(1H, s); ir (KCl) ν_{max} 3300-2500, 2980, 2880, 2650, 2550, 1690, 1630, 1570, 1440, 1370, 1270, 1230, 1050 cm^{-1}; ms *m/z* 230(M$^+$), 226, 213, 187, 174.

1-Bromo-4-(*trans*-4-propylcyclohexylacetyl)benzene **(39)**

trans-4-Propylcyclohexylacetyl chloride (9.00 g, 0.044 mol) was added dropwise to a stirred, cooled (0 °C) mixture of compound **38** (40 ml) and aluminium chloride (6.85 g, 0.050 mol). The mixture was stirred at 0 °C for 1 h, heated at 70 to 80 °C, cooled and poured into 18% hydrochloric acid. The product was extracted into chloroform (twice), and the combined organic extracts were washed with water. The chloroform was removed *in vacuo* and the residue was steam distilled to remove the excess of bromobenzene. The residue was extracted into chloroform (twice) and the combined organic extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a light-brown solid (12.05 g) which was recrystallised from ethanol to yield colourless crystals.

Yield 7.80 g (55%); mp 95-96 °C; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 0.95(3H, m), 1.15(4H, m), 1.30(2H, quint), 1.75(4H, M), 1.90(1H, m), 2.80(2H, d), 7.60(2H, d), 7.80(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1690, 1585, 1400, 1205, 1070, 1010, 990, 815 cm^{-1}; ms *m/z* 324(M$^+$), 322(M$^+$), 183, 181.

1-Bromo-4-(*trans*-4-propylcyclohexylethyl)benzene (**40**)

Triethylsilane (5.00 g, 0.043 mol) was added slowly dropwise to a stirred, cooled (0 °C) solution of compound **39** (5.50 g, 0.017 mol) in trifluoroacetic acid (30.0 g, 0.26 mol). The mixture was stirred at room temperature for 3.25 h (*i.e.*, until glc analysis revealed a complete reaction) and poured into water. The product was extracted into ether (twice) and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the brown liquid residue was distilled (Kugelrohr at 0.1 mmHg) to remove volatile impurities. The residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid.

Yield 4.30 g (82%); mp 38-39 °C; ^{1}H nmr ($CDCl_3$) δ 0.85(7H, m), 1.15(4H, m), 1.30(2H, quint), 1.45(2H, m), 1.75(4H, m), 2.55(2H, t), 7.05(2H, d), 7.35(2H, d); ir (KCl) ν_{max} 2920, 2850, 1490, 1450, 1075, 1015, 805 cm^{-1}; ms *m/z* 310(M$^+$), 308(M$^+$), 230, 171, 169.

4-(*trans*-4-propylcyclohexylethyl)benzoic acid (**41**)

A solution of n-butyllithium (5.20 ml, 2.5M in hexane, 0.013 mol) was added dropwise to a stirred, cooled (-78 °C) solution of compound **40** (4.00 g, 0.013 mol) in dry THF (90 ml). The mixture was maintained under these conditions for 35 min (*i.e.*, until glc analysis revealed a complete reaction) and then poured into a slurry of solid carbon dioxide and dry ether. The product was extracted into 10% sodium hydroxide (twice) and the combined basic extracts were acidified with 36% hydrochloric acid. The product was extracted into ether (twice), the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a colourless solid.

Yield 3.50 g (98%); mp 205-206 °C; ^{1}H nmr ($CDCl_3$) δ 0.90(7H, m), 1.15(4H, m), 1.30(2H, quint), 1.50(2H, q), 1.75(4H, m), 2.65(2H, t), 7.20(2H, d), 7.95(2H, d); ir (KCl) ν_{max} 3600-3200, 2920, 2860, 1680, 1610, 1425, 1320, 1295, 1180, 1130, 1025, 950, 765, 705 cm^{-1}; ms *m/z* 274(M^+), 257, 242, 230, 219.

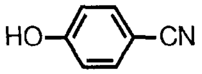
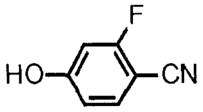
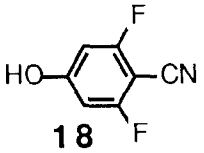
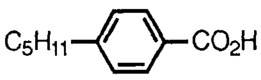
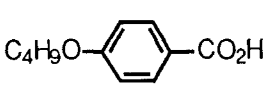
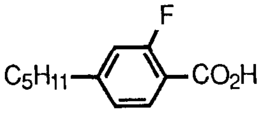
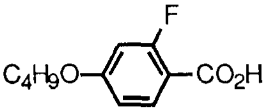
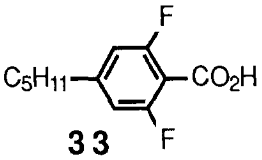
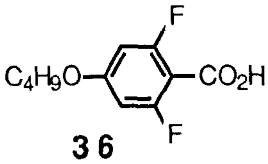
Fluoro-substituted 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates **(44-57)** and fluoro-substituted 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxy- benzoates **(59-74)**

A solution of *N*,*N*-dicyclohexylcarbodi-imide (DCC) (1.15 mol equivalent) in dry dichloromethane (40 ml) was added dropwise to a stirred solution of the appropriate carboxylic acid (1 mol equivalent), the appropriate phenol (1 mol equivalent) and 4-(*N*-pyrrolidino)pyridine (0.30 mol equivalent) in dry dichloromethane (50 ml) at room temperature. The mixture was stirred at room temperature overnight and the *N*,*N'*-dicyclohexylurea (DCU) was filtered off. The filtrate was washed successively with water, 5% acetic acid, water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography (silica gel / dichloromethane) to give a solid which was recrystallised from ethanol to yield colourless crystals.

The quantities of acids and phenols used are given in Tables 1 and 2 which show the phenol quantity as the upper figure and the acid quantity as the lower figure.

Table 1

Quantities of Acids and phenols [g (mmol)] used in the Preparation of Fluoro-substituted 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates (**44-57**)

PHENOL / ACID	 **43**	 **25**	 **18**
 **42**			1.0012 (6.46) **44** 1.2404 (6.46)
 **20**			1.1711 (7.56) **45** 1.4579 (7.51)
 **24**	0.7651 (6.43) **46** 1.3500 (6.43)	0.7832 (5.70) **48** 1.2010 (5.70)	1.1041 (7.12) **50** 1.4987 (7.14)
 **27**	0.7578 (6.37) **47** 1.3507 (6.37)	0.8737 (6.38) **49** 1.3517 (6.38)	1.1202 (7.23) **51** 1.5325 (7.23)
 **33**	0.6614 (5.56) **52** 1.2512 (5.50)	0.7511 (5.49) **54** 1.2511 (5.49)	1.0891 (7.03) **56** 1.6017 (7.03)
 **36**	0.5121 (4.30) **53** 0.9812 (4.26)	0.7521 (5.49) **55** 1.2513 (5.44)	1.0729 (6.92) **57** 1.5946 (6.93)

4-Cyano-3,5-difluorophenyl 4-pentylbenzoate (**44**)

Yield 0.70 g (33%); transitions (°C) K 29.5 (N -8.0) I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.70(2H, t), 7.05(2H, d), 7.35(2H, d), 8.05(2H, d); ir (KCl) ν_{max} 2980, 2940, 2860, 2240, 1740, 1640, 1610, 1580, 1490, 1450, 1420, 1260, 1180, 1050, 1020 cm^{-1}; ms *m/z* 329(M$^+$), 272, 175.

4-Cyano-3,5-difluorophenyl 4-butoxybenzoate **(45)**

Yield 1.96 g (79%); transitions (°C) K 71.5 [N 7.5] I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.05(2H, t), 6.98(2H, d), 7.05(2H, d), 8.10(2H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 2240, 1730, 1600, 1450, 1260, 1170, 1140, 1050, 1000 cm^{-1}; ms *m/z* 331(M$^+$), 288, 274, 177, 121.

4-Cyanophenyl 2-fluoro-4-pentylbenzoate **(46)**

Yield 0.81 g (41%); transitions (°C) K 65.5 (N 32.0) I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.04(1H, q), 7.10(1H, q), 7.38(2H, d), 7.74(2H, d), 8.00(1H, t); ir (KCl) ν_{max} 2950, 2860, 2230, 1750, 1730, 1630, 1600, 1500, 1220, 1170, 1050 cm^{-1}; ms *m/z* 311(M$^+$), 282, 268, 254, 242, 226.

4-Cyanophenyl 4-butoxy-2-fluorobenzoate **(47)**

Yield 1.08 g (54%); transitions (°C) K 90.0 (N 61.0) I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.85(2H, quint), 4.05(2H, t), 6.70(1H, q), 6.80(1H, q), 7.38(2H, d), 7.74(2H, d), 8.05(1H, t); ir (KCl) ν_{max} 2960, 2880, 2240, 1750, 1730, 1620, 1600, 1510, 1280, 1220, 1180, 1130, 1040, 1010 cm^{-1}; ms *m/z* 313(M$^+$), 270, 256, 231, 195.

4-Cyano-3-fluorophenyl 2-fluoro-4-pentylbenzoate **(48)**

Yield 0.46 g (25%); transitions (°C) K 39.5 (N -3.0) I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.05(1H, q), 7.12(1H, q), 718-7.25(2H, m), 7.70(1H, q), 8.00(1H, t); ir (KCl) ν_{max} 2980, 2940, 2860, 2240, 1750, 1730, 1620, 1590, 1500, 1470, 1290, 1250, 1150, 1040 cm^{-1}; ms *m/z* 329(M$^+$), 272, 193, 179, 136, 108.

4-Cyano-3-fluorophenyl 4-butoxy-2-fluorobenzoate **(49)**

Yield 1.46 g (69%); transitions (°C) K 55.0 (N 21.5) I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.85(2H, quint), 4.05(2H, t), 6.70(1H, q), 6.80(1H, q), 7.16-7.26(2H, m), 7.65(1H, q), 8.00(1H, t); ir (KCl) ν_{max} 2970, 2880, 2240, 1750, 1730, 1620, 1590, 1510, 1440, 1350, 1250, 1150, 1030, 1010 cm^{-1}; ms *m/z* 331(M$^+$), 287, 274, 246, 218.

4-Cyano-3,5-difluorophenyl 2-fluoro-4-pentylbenzoate **(50)**

Yield 1.10 g (44%); transitions (°C) K 55.0 (N -20.5) I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.05(1H, q), 7.07(2H, d), 7.12(1H, q), 7.95(1H, t); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1750, 1640, 1620, 1580, 1500, 1470, 1290, 1250, 1040 cm^{-1}; ms *m/z* 347(M$^+$), 290, 193.

4-Cyano-3,5-difluorophenyl 4-butoxy-2-fluorobenzoate **(51)**

Yield 1.80 g (71%); transitions (°C) K 68.5 [N -6.0] I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.05(2H, t), 6.70(1H, q), 6.79(1H, oct), 7.05(2H, d), 8.00(1H, t); ir (KCl) ν_{max} 2960, 2880, 2240, 1755, 1620, 1450, 1350, 1240, 1220, 840 cm^{-1}; ms *m/z* 349(M$^+$), 306, 292.

4-Cyanophenyl 2,6-difluoro-4-pentylbenzoate **(52)**

Yield 1.44 g (80%); transitions (°C) K 74.5 [N -18.0] I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 6.86(2H, d), 7.38(2H, d), 7.75(2H, d); ir (KCl) ν_{max} 2940, 2240, 1750, 1635, 1600, 1500, 1440, 1295, 1260, 1140, 1070, 1040 cm^{-1}; ms *m/z* 329(M$^+$), 272, 211, 195.

4-Cyanophenyl 4-butoxy-2,6-difluorobenzoate **(53)**

Yield 0.86 g (61%); transitions (°C) K 101.0 [N 25.0] I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.55(2H, d), 7.35(2H, d), 7.70(2H, d); ir (KCl) ν_{max} 2950, 2900, 2250, 1750, 1640, 1600, 1580, 1500, 1450, 1360, 1260, 1160, 1080 cm^{-1}; ms *m/z* 331(M$^+$), 213, 157.

4-Cyano-3-fluorophenyl 2,6-difluoro-4-pentylbenzoate **(54)**

Yield 1.05 g (55%); transitions (°C) K 32.0 [N -45.0] I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 6.86(2H, d), 7.20-7.28(2H, m), 7.70(1H, q); ir (KCl) ν_{max} 2950, 2880, 2250, 1750, 1640, 1500, 1440, 1430, 1250, 1150, 1070, 1040 cm^{-1}; ms *m/z* 347(M$^+$), 210, 188, 181, 167, 154.

4-Cyano-3-fluorophenyl 4-butoxy-2,6-difluorobenzoate **(55)**

Yield 1.04 g (55%); transitions (°C) K 56.0 (N -1.5) I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.55(2H, d), 7.18-7.24(2H, m), 7.70(1H, q); ir (KCl) ν_{max} 2980, 2880, 2240, 1750, 1640, 1620, 1580, 1500, 1440, 1360, 1250, 1150, 1050 cm^{-1}; ms *m/z* 349(M$^+$), 330, 306, 292, 264, 244.

4-Cyano-3,5-difluorophenyl 2,6-difluoro-4-pentylbenzoate **(56)**

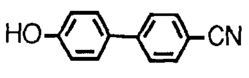
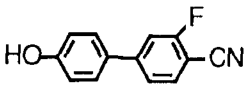
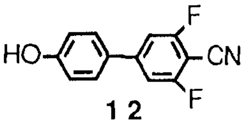
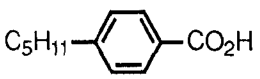
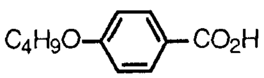
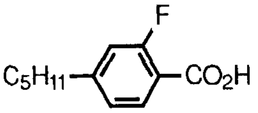
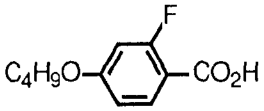
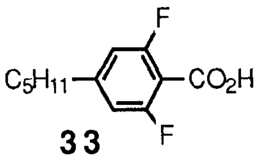
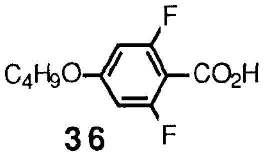
Yield 2.22 g [87% (not recrystallised)]; transitions (°C) K 36.5 [N -67.0] I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(4H, m), 1.65(2H, quint), 2.65(2H, t), 6.87(2H, d), 7.09(2H, d); ir (KCl) ν_{max} 2960, 2880, 2240, 1760, 1640, 1580, 1450, 1250, 1130, 1050 cm^{-1}; ms *m/z* 365(M$^+$), 322, 308, 281.

4-Cyano-3,5-difluorophenyl 4-butoxy-2,6-difluorobenzoate **(57)**

Yield 1.47 g (58%); transitions (°C) K 63.0 [N 31.5] I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.55(2H, d), 7.05(2H, d); ir (KCl) ν_{max} 2960, 2880, 2240, 1735, 1630, 1570, 1450, 1350, 1260, 1170, 1140, 1050 cm^{-1}; ms *m/z* 367(M$^+$), 324, 310.

Table 2

Quantities of Acids and Phenols [g (mmol)] used in the Preparation of Fluoro-substituted 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxy- benzoates (**59-74**)

PHENOL ACID	 **58**	 **11**	 **12**
 **42**		1.0012 (4.69) **59** 0.9011 (4.69)	0.8910 (3.85) **61** 0.7403 (3.85)
 **20**		1.3004 (6.10) **60** 1.1820 (6.08)	1.4012 (6.06) **62** 1.1700 (6.03)
 **24**	0.9753 (5.00) **63** 1.0651 (5.07)	1.1176 (5.25) **65** 1.1004 (5.24)	1.1118 (4.81) **67** 1.0120 (4.82)
 **27**	1.2517 (6.42) **64** 1.3458 (6.37)	1.2501 (5.87) **66** 1.2411 (5.85)	1.3591 (5.88) **68** 1.2497 (5.89)
 **33**	1.0267 (5.27) **69** 1.2012 (5.26)	1.0811 (5.07) **71** 1.1503 (5.04)	1.2201 (5.28) **73** 1.2001 (5.26)
 **36**	0.8157 (4.18) **70** 0.9621 (4.18)	1.0707 (5.04) **72** 1.1606 (5.04)	1.2591 (5.45) **74** 1.2519 (5.44)

4-Cyano-3-fluorobiphenyl-4'-yl 4-pentylbenzoate (**59**)

Yield 1.40 (77%); transitions (°C) K 123.5 N 198.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.40(4H, m), 1.60(2H, quint), 2.60(2H, t), 7.32(2H, d), 7.35(2H, d), 7.43(1H, q), 7.48(1H, q), 7.64(2H, d), 7.68(1H, q), 8.12(2H, d);

ir (KCl) ν_{max} 2940, 2890, 2250, 1740, 1620, 1560, 1480, 1260, 1210, 1170, 1060, 1030 cm^{-1}; ms *m/z* 387(M$^+$), 329, 314, 297, 286.

4-Cyano-3-fluorobiphenyl-4'-yl 4-butoxybenzoate **(60)**

Yield 1.75 g (74%); transitions (°C) K 135.0 N 237.0 I;^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.55(2H, sext), 1.85(2H, quint), 4.05(2H, t), 7.00(2H, d), 7.35(2H, d), 7.43(1H, q), 7.48(1H, q), 7.63(2H, d), 7.70(1H, q), 8.15(2H, d); ir (KCl) ν_{max} 2980, 2880, 2240, 1720, 1600, 1510, 1490, 1270, 1210, 1170, 1060 cm^{-1}; ms *m/z* 389(M$^+$), 346, 304, 177, 121.

4-Cyano-3,5-difluorobiphenyl-4'-yl 4-pentylbenzoate **(61)**

Yield 0.95 g (61%); transitions (°C) K 96.5 N 150.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.70(2H, quint), 2.70(2H, t), 7.28(2H, d), 7.33(2H, d), 7.37(2H, d), 7.62(2H, d), 8.10(2H, d); ir (KCl) ν_{max} 2950, 2250, 1735, 1640, 1610, 1560, 1490, 1205, 1175, 1070, 1050 cm^{-1}; ms *m/z* 405(M$^+$), 391, 373, 361, 348, 333.

4-Cyano-3,5-difluorobiphenyl-4'-yl 4-butoxybenzoate **(62)**

Yield 2.15 g (88%); transitions (°C) K 114.0 N 195.0 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.55(2H, sext), 1.85(2H, quint), 4.05(2H, t), 7.00(2H, d), 7.28(2H, d), 7.35(2H, d), 7.62(2H, d), 8.15(2H, d); ir (KCl) ν_{max} 2980, 2940, 2250, 1720, 1630, 1560, 1510, 1490, 1270, 1210, 1170, 1060 cm^{-1}; ms *m/z* 407(M$^+$), 230, 177, 121.

4-Cyanobiphenyl-4'-yl 2-fluoro-4-pentylbenzoate **(63)**

Yield 1.55 g (79%); transitions (°C) K 103.0 N 225.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.70(2H, t), 7.04(1H, q), 7.11(1H, q), 7.35(2H, d), 7.65(2H, d), 7.70(2H, d), 7.75(2H, d), 8.02(1H, t); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1750, 1730, 1620, 1610, 1490, 1200, 1050 cm^{-1}; ms *m/z* 387(M$^+$), 373, 221, 209, 193.

4-Cyanobiphenyl-4'-yl 4-butoxy-2-fluorobenzoate **(64)**

Yield 1.80 g (73%); transitions (°C) K 94.0 N 259.5 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.85(2H, quint), 4.05(2H, t), 6.70(1H, q), 6.80(1H, q), 7.35(2H, d), 7.65(2H, d), 7.70(2H, d), 7.75(2H, d), 8.05(1H, t); ir (KCl) ν_{max} 2970, 2880, 2240, 1740, 1720, 1620, 1490, 1270, 1240, 1170, 1010 cm^{-1}; ms *m/z* 389(M$^+$), 346, 332, 304.

4-Cyano-3-fluorobiphenyl-4'-yl 2-fluoro-4-pentylbenzoate **(65)**

Yield 0.80 g (38%); transitions (°C) K 112.5 N 187.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.70(2H, t), 7.05(1H, q), 7.11(1H, q), 7.37(2H, d), 7.43(1H, q), 7.49(1H, q), 7.64(2H, d), 7.70(1H, q), 8.02(1H, t); ir (KCl) ν_{max} 2980, 2940, 2860, 2240, 1750, 1730, 1620, 1490, 1200, 1020 cm^{-1}; ms *m/z* 405(M$^+$), 348, 212, 193.

4-Cyano-3-fluorobiphenyl-4'-yl 4-butoxy-2-fluorobenzoate **(66)**

Yield 1.17 g (49%); transitions (°C) K 115.0 N 219.5 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.85(2H, quint), 4.05(2H, t), 6.72(1H, q), 6.80(1H, q), 7.35(2H, d), 7.42(1H, q), 7.48(1H, q), 7.63(2H, d), 7.70(1H, q), 8.05(1H, t); ir (KCl) ν_{max} 2980, 2940, 2880, 2240, 1730, 1710, 1620, 1490, 1270, 1210, 1190 cm^{-1}; ms *m/z* 407(M$^+$), 364, 322, 212, 195.

4-Cyano-3,5-difluorobiphenyl-4'-yl 2-fluoro-4-pentylbenzoate **(67)**

Yield 1.82 g (89%); transitions (°C) K 98.0 N 143.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.05(1H, q), 7.11(1H, q), 7.28(2H, d), 7.38(2H, d), 7.63(2H, d), 8.02(1H, t); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1750, 1730, 1630, 1490, 1290, 1200, 1050 cm^{-1}; ms *m/z* 423(M$^+$), 366, 352, 338, 322.

4-Cyano-3,5-difluorobiphenyl-4'-yl 4-butoxy-2-fluorobenzoate **(68)**

Yield 1.72 g (69%); transitions (°C) K 104.0 N 184.0 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.85(2H, quint), 4.05(2H, t), 6.70(1H, q), 6.80(1H, q), 7.28(2H, d), 7.38(2H, d), 7.63(2H, d), 8.05(1H, t); ir (KCl) ν_{max} 2980, 2880, 2240, 1735, 1710, 1630, 1480, 1280, 1260, 1040 cm^{-1}; ms *m/z* 425(M$^+$), 382, 340.

4-Cyanobiphenyl-4'-yl 2,6-difluoro-4-pentylbenzoate **(69)**

Yield 1.81 g (85%); transitions (°C) K 109.5 N 191.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 6.85(2H, d), 7.38(2H, d), 7.64(2H, d), 7.68(2H, d), 7.75(2H, d); ir (KCl) ν_{max} 2960, 2880, 2240, 1740, 1640, 1495, 1260, 1200, 1075, 1040 cm^{-1}; ms *m/z* 405(M$^+$), 347, 211, 194.

4-Cyanobiphenyl-4'-yl 4-butoxy-2,6-difluorobenzoate **(70)**

Yield 0.92 g (54%); transitions (°C) K 94.0 N 223.0 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.55(2H, d), 7.35(2H, d), 7.64(2H, d), 7.68(2H, d), 7.75(2H, d); ir (KCl) ν_{max} 2980, 2880, 2240, 1740, 1640, 1620, 1450, 1260, 1200, 1050 cm^{-1}; ms *m/z* 407(M$^+$), 364, 350, 336, 258.

4-Cyano-3-fluorobiphenyl-4'-yl 2,6-difluoro-4-pentylbenzoate **(71)**

Yield 1.31 g (61%); transitions (°C) K 116.5 N 158.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 6.85(2H, d), 7.38(2H, d), 7.43(1H, q), 7.48(1H, q), 7.65(2H, d), 7.70(1H, q); ir (KCl) ν_{max} 2980, 2940, 2880, 2250, 1740, 1640, 1490, 1260, 1200, 1070, 1040 cm^{-1}; ms *m/z* 423(M$^+$), 211, 184, 154.

4-Cyano-3-fluorobiphenyl-4'-yl 4-butoxy-2,6-difluorobenzoate **(72)**

Yield 1.69 g (79%); transitions (°C) K 103.0 N 194.0 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.55(2H, d), 7.38(2H, d), 7.43(1H, q), 7.48(1H, q), 7.65(2H, d), 7.70(1H, q); ir (KCl) ν_{max} 2980, 2890, 2240, 1740, 1640, 1450, 1260, 1200, 1050 cm^{-1}; ms *m/z* 425(M$^+$), 382, 368, 340.

4-Cyano-3,5-difluorobiphenyl-4'-yl 2,6-difluoro-4-pentylbenzoate **(73)**

Yield 1.93 g (83%); transitions (°C) K 89.0 N 121.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 6.86(2H, d), 7.28(2H, d), 7.40(2H, d), 7.64(2H, d); ir (KCl) ν_{max} 2950, 2930, 2860, 2250, 1740, 1640, 1490, 1260, 1200, 1070, 1040 cm^{-1}; ms *m/z* 442(M$^+$), 384, 340, 211.

4-Cyano-3,5-difluorobiphenyl-4'-yl 4-butoxy-2,6-difluorobenzoate **(74)**

Yield 1.51 g (63%); transitions (°C) K 102.0 N 161.5 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.85(2H, quint), 4.05(2H, t), 6.55(2H, d), 7.28(2H, d), 7.40(2H, d), 7.64(2H, d); ir (KCl) ν_{max} 2980, 2880, 2240, 1735, 1640, 1440, 1260, 1200, 1080, 1040 cm^{-1}; ms *m/z* 443(M$^+$), 400, 244, 230, 213.

4-Cyanophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoate **(75)**

Quantities: compound **41** (0.90 g, 3.28 mmol), compound **43** (0.40 g, 3.36 mmol).

See p 122 for experimental procedure.

Yield 0.67 g (54%); transitions (°C) K 90.0 N 194.0 I; ^{1}H nmr (CDCl$_3$) δ 0.85(7H, m), 1.15(4H, m), 1.30(2H, quint), 1.55(2H, m), 1.80(4H, m), 2.70(2H, t), 7.32(2H, d), 7.37(2H, d), 7.76(2H, d), 8.10(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1745, 1605, 1500, 1265, 1210, 1180, 1065, 1020, 890, 560 cm^{-1}; ms *m/z* 257, 250, 236, 227.

4-Cyano-3-fluorophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoate **(76)**

Quantities: compound **41** (1.15 g, 4.20 mmol), compound **25** (0.58 g, 4.23 mmol).

See p 122 for experimental procedure.

Yield 1.24 g (75%); transitions (°C) K 59.0 N 167.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(7H, m), 1.15(4H, m), 1.30(2H, quint), 1.55(2H, m), 1.80(4H, m), 2.75(2H, t), 7.20(2H, m), 7.34(2H, d), 7.70(1H, q), 8.09(2H, d); ir (KCl) ν_{max} 2960, 2940, 2850, 2240, 1750, 1610, 1590, 1500, 1435, 1240, 1180, 1150, 1105, 1050, 1020, 970, 905, 885, 700 cm^{-1}; ms *m/z* 257, 241, 227, 213, 199.

4-Cyano-3,5-difluorophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoate **(77)**

Quantities: compound **41** (1.15 g, 4.20 mmol), compound **25** (0.66 g, 4.26 mmol).

See p 122 for experimental procedure.

Yield 0.78 g (45%); transitions (°C) K 55.0 N 134.5 I; ^{1}H nmr (CDCl$_3$) δ 0.85(7H, m), 1.15(4H, m), 1.30(2H, quint), 1.55(2H, m), 1.80(4H, m), 2.70(2H, t), 7.06(2H, d), 7.34(2H, d), 8.06(2H, d); ir (KCl) ν_{max} 2960, 2920, 2850, 2250, 1750, 1735, 1645, 1610, 1590, 1500, 1450, 1255, 1135, 1060, 1020 cm^{-1}; ms *m/z* 257, 241, 227, 213, 155.

4-Cyano-3-fluorobiphenyl-4'-yl hexanoate **(79)**

Quantities: compound **78** (0.7068 g, 6.09 mmol), compound **11** (1.3000 g, 6.10 mmol).

See p 122 for experimental procedure.

Yield 1.29 g (68%); transitions (°C) K 35.5 (N 25.0) I; ^{1}H nmr (CDCl$_3$) δ 0.95(3H, t), 1.35(4H, m), 1.80(2H, quint), 2.55(2H, t), 7.20(2H, d), 7.40(2H, q), 7.60(2H, d), 7.70(1H, q); ir (KCl) ν_{max} 2960, 2940, 2880, 2240, 1760, 1620, 1560, 1490, 1210, 1140 cm^{-1}; ms *m/z* 311(M$^+$), 213, 195, 184.

4-Cyano-3,5-difluorobiphenyl-4'-yl hexanoate **(80)**

Quantities: compound **78** (0.6761 g, 5.83 mmol), compound **12** (1.3502 g, 5.84 mmol).

See p 122 for experimental procedure.

Yield 1.10 g (57%); transitions (°C) K 58.0 I; ^{1}H nmr ($CDCl_3$) δ 0.95(3H, t), 1.35(4H, m), 1.80(2H, quint), 2.55(2H, t), 7.25(4H, 2xd), 7.55(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1755, 1635, 1560, 1490, 1440, 1400, 1210, 1150, 1040 cm^{-1}; ms *m/z* 329(M^+), 231, 213, 202.

4-Cyanobiphenyl-4'-yl heptoxyethanoate **(82)**

Quantities: compound **81** (1.0910 g, 6.27 mmol), compound **58** (1.2231 g, 6.27 mmol).

See p 122 for experimental procedure.

Yield 0.60 g (27%); transitions (°C) K 51.5 (S_A 40.5 N 41.5) I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(8H, m), 1.65(2H, quint), 3.65(2H, t), 4.35(2H, s), 7.25(2H, d), 7.60(2H, d), 7.65(2H, d), 7.75(2H, d); ir (KCl) ν_{max} 2940, 2860, 2240, 1775, 1760, 1495, 1135, 825 cm^{-1}; ms *m/z* 351(M^+), 323, 293, 195.

1-Bromo-4-hexoxybenzene (**84**)

Quantities: compound **83** (71.0 g, 0.41 mol), 1-bromohexane (60.0 g, 0.36 mol), potassium carbonate (120.0 g, 0.87 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 79.4 g (86%); bp 100-110 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.50(6H, m), 1.80(2H, quint), 4.00(2H, t), 7.00(2H, d), 7.70(2H, d); ir (film) ν_{max} 2960, 2940, 2880, 1590, 1490, 1290, 1250, 1170, 1070, 1000, 820 cm^{-1}; ms *m/z* 258(M^+), 256(M^+), 174, 172.

1-Bromo-4-octoxybenzene (**85**)

Quantities: compound **83** (64.5 g, 0.37 mol), 1-bromo-octane (60.0 g, 0.31 mol), potassium carbonate (103.5 g, 0.75 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 86.5 g (98%); bp 145 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(8H, m), 1.40(2H, quint), 1.75(2H, quint), 3.95(2H, t), 6.75(2H, d), 7.35(2H, d); ir (film) ν_{max} 2950, 2860, 1600, 1585, 1495, 1475, 1290, 1250, 1175, 1080, 1005, 835 cm^{-1}; ms *m/z* 286(M^+), 284(M^+), 174, 172.

4-Hexoxyphenylboronic acid (**86**)

A solution of the Grignard reagent, prepared from compound **84** (72.0 g, 0.28 mol) and magnesium (7.75 g, 0.319 mol) in dry THF (220 ml) was added dropwise to a stirred, cooled (-78 °C) solution of tri-isopropyl borate (109.0 g, 0.58 mol) in dry THF (40 ml) under dry nitrogen. The stirred mixture was allowed to warm to room temperature overnight and stirred with 10% hydrochloric acid (320 ml) at room temperature for 1 h. The product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to afford a colourless solid.

Yield 61.2 g (99%); mp 80-85 °C; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.40(6H, m), 1.80(2H, quint), 4.10(2H, t), 7.20(2H, d), 8.40(2H, d), no obvious OH absorption; ir (KCl) ν_{max} 3500-3100, 2960, 2940, 2880, 1600, 1570, 1420, 1380, 1350, 1250, 1170, 1030, 840 cm^{-1}; ms *m/z* 382, 359, 342, 306, 298, 290, 281, 253, 239, 223, 214, 205.

4-Octoxyphenylboronic acid **(87)**

Quantities: compound **85** (42.0 g, 0.15 mol), magnesium (4.12 g, 0.170 mol), tri-isopropyl borate (53.3 g, 0.29 mol).

The experimental procedure was the same as for compound **86**.

Yield 36.1 g (98%); ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.95(2H, t), 7.75(1H, d), 8.15(1H, d), no obvious OH absorption; ir (KCl) ν_{max} 2950, 2860, 1610, 1360, 1255, 1180 cm^{-1}; ms *m/z* 280, 265, 248, 232, 222, 213, 206, 196, 185.

1-Bromo-4-pentanoylbenzene **(88)**

Pentanoyl chloride (50.0 g, 0.41 mol) was added dropwise to a stirred, cooled (0 °C) mixture of compound **38** (150 ml) and aluminium chloride (62.0 g, 0.46 mol). The mixture was stirred at 0 °C for 1 h, heated at 80 °C for 2 h, cooled and poured into 18% hydrochloric acid. The product was extracted into chloroform (twice), the combined organic extracts were washed with water and steam distilled to remove chloroform and the excess of bromobenzene. The residue was extracted into chloroform (twice), the combined organic extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was distilled to yield a colourless solid.

Yield 78.1 g (78%); bp 180-184 °C at 20 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.60(4H, m), 3.00(2H, t), 7.80(2H, d), 8.00(2H, d); ir (KCl) ν_{max} 2960, 2880, 1685, 1585, 1400, 1070, 1010, 980 cm^{-1}; ms *m/z* 242(M^+), 240(M^+), 213, 198, 185.

1-Bromo-4-heptanoylbenzene **(89)**

Quantities: heptanoyl chloride (60.0 g, 0.40 mol), compound **38** (150 ml), aluminium chloride (62.0 g, 0.46 mol).

The experimental procedure was as described for the preparation of compound **88**. Yield 107.0 g (99%); bp 130-135 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(6H, m), 1.75(2H, quint), 2.95(2H, t), 7.60(2H, d), 7.85(2H, d); ir (KCl) ν_{max} 2980, 2950, 2910, 2880, 1680, 1590, 1470, 1400, 1200, 1070, 1010, 980, 840, 800, 730 cm^{-1}; ms *m/z* 270(M^+), 268(M^+), 213, 200, 183, 157, 132.

1-Bromo-4-nonanoylbenzene **(90)**

Quantities: nonanoyl chloride (13.90 g, 0.079 mol), compound **38** (55 ml), aluminium chloride (12.10 g, 0.091 mol).

The experimental procedure was as described for the preparation of compound **88**. Yield 23.00 g (98%); bp 138-140 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(10H, m), 1.70(2H, quint), 2.90(2H, t), 7.60(2H, d), 7.80(2H, d); ir (KCl) ν_{max} 2940, 2860, 1690, 1590, 1470, 1380, 1070, 1005, 810 cm^{-1}; ms *m/z* 298(M^+), 296(M^+), 200, 198, 185, 183, 157, 155.

1-Bromo-4-pentylbenzene **(91)**

A mixture of compound **88** (77.1 g, 0.32 mol), hydrazine hydrate (46.4 g, 0.93 mol) and potassium hydroxide (59.0 g, 1.05 mol) in diethylene glycol (250 ml) was heated at 130 °C for 2 h, the excess of hydrazine hydrate was distilled off and the temperature was raised to 200 °C for 2 h. The cooled mixture was poured into 18% hydrochloric acid, the product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was distilled to yield a colourless liquid.

Yield 58.1 g (80%); bp 145-148 °C at 20 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.60(2H, t), 7.10(2H, d), 7.50(2H, d); ir (film) ν_{max} 2960, 2930, 2880, 1490, 1410, 1075, 1015, 830 cm^{-1}; ms *m/z* 228(M^+), 226(M^+), 195, 185, 171.

1-Bromo-4-heptylbenzene **(92)**

Quantities: compound **89** (106.0 g, 0.39 mol), hydrazine hydrate (56.5 ml, 58.20 g, 1.16 mol), potassium hydroxide (74.0 g, 1.32 mol).

The experimental procedure was as described for the preparation of compound **91**. Yield 59.0 g (58%); bp 105-115 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.25(8H, m), 1.55(2H, quint), 2.50(2H, t), 7.00(2H, d), 7.35(2H, d); ir (film) ν_{max} 2950, 2860, 1490, 1410, 1075, 1015, 800 cm^{-1}; ms *m/z* 256(M^+), 254(M^+), 169, 103, 91.

1-Bromo-4-nonylbenzene **(93)**

Quantites: compound **90** (22.00 g, 0.074 mol), hydrazine hydrate (10.70 ml, 11.00 g, 0.22 mol), potassium hydroxide (13.70 g, 0.245 mol).

The experimental procedure was as described for the preparation of compound **91**. Yield 8.38 g (40%); bp 124-126 °C at 0.1 mmHg;^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.25(12H, s), 1.55(2H, quint), 2.55(2H, t), 7.03(2H, d), 7.38(2H, d); ir (film) ν_{max} 2960, 2940, 2860, 1595, 1490, 1470, 1405, 1250, 1075, 1015, 820, 800 cm^{-1}; ms *m/z* 284(M^+), 282(M^+), 171, 169.

4-Pentylphenylboronic acid **(94)**

Quantities: compound **91** (24.00 g, 0.106 mol), magnesium (2.95 g, 0.121 mol), tri-isopropyl borate (39.8 g, 0.21 mol).

The experimental procedure was as described for the preparation of compound **86**. Yield 19.30 g(95%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.40(4H, m), 1.65(2H, quint), 2.70(2H, t), 7.35(4H, m), no obvious OH absorption; ir (KCl) ν_{max} 3600-3200, 2960, 2940, 2860, 1610, 1410, 1370-1240, 1310, 1180, 1020, 700 cm^{-1}; ms *m/z* 247, 233, 230, 217, 211, 207.

4'-Pentylbiphenyl-4-ylboronic acid (96)

Quantities: compound **95** (25.00 g, 0.083 mol), magnesium (2.25 g, 0.093 mol), tri-isopropyl borate (31.0 g, 0.16 mol).

The experimental procedure was as described for the preparation of compound **86**.

Yield 21.00 g (98%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.25(2H, d), 7.50-7.60(4H, m), 7.65(1H, d), 7.90(1H, d), no obvious OH absorption; ir (KCl) ν_{max} 3600-3100, 2960, 2940, 2860, 1610, 1450-1300, 1005, 815 cm^{-1}; ms *m/z* 446, 389, 293, 240, 224, 195, 183, 167, 152.

4-Hexoxy-4''-pentylterphenyl (97)

A solution of compound **86** (1.12 g, 5.05 mmol) in ethanol (15 ml) was added to a stirred mixture of compound **95** (1.15 g, 3.80 mmol) and tetrakis(triphenylphosphine)palladium(0) (0.2646 g, 0.23 mmol) in benzene (30 ml) and 2M sodium carbonate (30 ml) at room temperature under dry nitrogen. The stirred mixture was heated under reflux (~100 °C) for 23 h (*i.e.*, until glc and tlc analysis revealed a complete reaction). The product was extracted into ether (twice) and the combined ethereal extracts were washed with brine and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethyl acetate to yield colourless crystals.

Yield 0.96 g (63%); transitions (°C) K 205.0 S_B 216.0 S_A 228.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.27(2H, d), 7.55(2H, d), 7.57(2H, d), 7.64(4H, 2xd); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1495, 1250, 810 cm^{-1}; ms *m/z* 400(M$^+$), 371, 357, 343, 332.

4-Octoxy-4''-pentylterphenyl (98)

Quantities: Compound **95** (1.15 g, 3.80 mmol), compound **87** (1.25 g, 5.00

mmol), tetrakis(triphenylphosphine)palladium(0) (0.2401 g, 0.21 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethyl acetate to yield colourless crystals.

Yield 1.02 g (63%); transitions (°C) K 194.5 S_B 211.0 S_A 221.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.27(2H, d), 7.55(2H, d), 7.57(2H, d), 7.64(4H, 2xd); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1495, 1255, 805 cm^{-1}; ms *m/z* 428(M^+), 411, 400, 385, 371, 329, 316.

1-Bromo-3-fluoro-4-hexoxybenzene (**100**)

Quantities: compound **99** (10.00 g, 0.052 mol), 1-bromohexane (10.37 g, 0.063 mol), potassium carbonate (14.50 g, 0.105 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 13.71 g (96%); bp 110-112 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.80(1H, t), 7.15(1H, oct), 7.20(1H, q); ir (film) ν_{max} 2980, 2950, 2880, 1595, 1510, 1475, 1420, 1315, 1290, 1275, 1140, 1030, 885, 870, 810 cm^{-1}; ms *m/z* 276(M^+), 275, 274(M^+), 273, 202, 189.

1-Bromo-3-fluoro-4-octoxybenzene (**101**)

Quantities: compound **99** (10.00 g, 0.052 mol), 1-bromo-octane (12.00 g, 0.062 mol), potassium carbonate (14.5 g, 0.105 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 15.40 g (98%); bp 120-122 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ

0.90(3H, t), 1.30(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.80(1H, t), 7.15(1H, oct), 7.20(1H, q); ir (film) ν_{max} 2980, 2940, 2860, 1505, 1480, 1410, 1310, 1270, 1210, 1170, 1030, 885, 870, 800 cm^{-1}; ms *m/z* 304(M^+), 302(M^+), 192, 190.

3-Fluoro-4-hexoxy-4"-pentylterphenyl **(102)**

Quantities: compound **100** (1.00 g, 3.64 mmol), compound **96** (1.27 g, 4.74 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2424 g, 0.21 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (1:1) to yield colourless crystals.

Yield 0.77 g (51%); transitions (°C) K ? S_G 160.0 S_C 162.0 S_A 201.0 I; ^1H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.50(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.05(2H, t), 7.03(1H, t), 7.27(2H, d), 7.33(1H, q), 7.37(1H, q), 7.55(2H, d), 7.58(2H, d), 7.65(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1620, 1500, 1400, 1375, 1350, 1190, 1140, 805 cm^{-1}; ms *m/z* 418(M^+), 334, 300, 277, 243.

3-Fluoro-4-octoxy-4"-pentylterphenyl **(103)**

Quantities: compound **101** (1.36 g, 4.49 mmol), compound **96** (1.45 g, 5.41 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2101 g, 0.18 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 1.75 g (87%); transitions (°C) K ? S_G 146.0 S_B 158.0 S_A 195.0 I; ^1H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.05(2H, t), 7.02(1H, t), 7.26(2H, d), 7.33(1H, q), 7.37(1H, q), 7.54(2H, d), 7.58(2H, d), 7.64(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1625, 1525, 1500, 1485, 1405, 1305, 1275, 1250, 1195, 1140, 880, 810 cm^{-1}; ms *m/z* 446(M$^+$), 389, 334, 277.

1-Bromo-2-fluoro-4-hexoxybenzene (**105**)

Quantities: compound **104** (9.00 g, 0.047 mol), 1-bromohexane (9.33 g, 0.057 mol), potassium carbonate (13.50 g, 0.098 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 12.71 g (98%); bp 100-105 °C at 0.1 mmHg; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(4H, m), 1.40(2H, quint), 1.75(2H, quint), 3.90(2H, t), 6.55(1H, oct), 6.65(1H, q), 7.35(1H, t); ir (film) ν_{max} 2950, 2880, 1610, 1590, 1490, 1470, 1330, 1300, 1260, 1170, 1020, 840, 650 cm^{-1}; ms *m/z* 276(M$^+$), 274(M$^+$), 190, 173, 161, 151.

1-Bromo-2-fluoro-4-octoxybenzene (**106**)

Quantities: compound **104** (6.00 g, 0.031 mol), 1-bromo-octane (7.30 g, 0.038 mol), potassium carbonate (10.00 g, 0.072 mol).

The experimental procedure was as described for the preparation of compound **26**. and the crude product was distilled.

Yield 9.01 g (96%); bp 140-142 °C at 0.1 mmHg; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(10H, m), 1.70(2H, quint), 3.90(2H, t), 6.55(1H, oct), 6.65(1H, q), 7.35(1H, t); ir (film) ν_{max} 2940, 2860, 1605, 1585, 1490, 1470, 1325, 1295, 1170, 1145 cm^{-1}; ms *m/z* 304(M$^+$), 302(M$^+$), 191, 189.

2-Fluoro-4-hexoxy-4"-pentylterphenyl (**107**)

Quantities: compound **105** (1.50 g, 5.45 mmol), compound **96** (1.90 g, 7.10 mmol), tetrakis(triphenylphosphine)palladium(0) (0.5010 g, 0.43 mmol).

The experimental procedure was as described for the preparation of compound **97**.

The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1), to yield colourless crystals.

Yield 1.46 g (64%);

transitions (°C) K 83.5 (S_K 48.5 S_J 62.0) S_C 105.0 N 166.0 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 3.95(2H, t), 6.72(1H, q), 6.78(1H, q), 7.27(2H, d), 7.38(1H, t), 7.54(2H, d), 7.58(2H, d), 7.64(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1625, 1500, 1400, 1335, 1320, 1240, 1175, 1120, 1030, 810 cm^{-1}; ms *m/z* 418(M$^+$), 361, 334, 277.

2-Fluoro-4-octoxy-4''-pentylterphenyl (**108**)

Quantities: compound **106** (2.00 g, 6.60 mmol), compound **96** (2.30 g, 8.58 mmol), tetrakis(triphenylphosphine)palladium(0) (0.6003 g, 0.52 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 2.30 g (78%);

transitions (°C) K 69.0 (S_K 25.0 S_J 43.0) S_C 119.0 N 158.0 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 3.95(2H, t), 6.72(1H, q), 6.78(1H, q), 7.27(2H, d), 7.38(1H, t), 7.54(2H, d), 7.58(2H, d), 7.64(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1640, 1500, 1400, 1335, 1320, 1240, 1175, 1120, 810 cm^{-1}; ms *m/z* 446(M$^+$), 418, 403, 389, 361, 334, 277.

2-Fluoro-4,4''-dipentylterphenyl (**110**)

Quantities: compound **109** (1.10 g, 3.43 mmol), compound **94** (0.8721 g, 4.54 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2212 g, 0.19 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 0.89 g (67%); transitions (°C) K 72.5 S_C 80.0 N 136.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, t), 1.35(8H, m), 1.65(4H, quint), 2.60(4H, 2xt), 6.99(1H, q), 7.03(1H, q), 7.27(2H, d), 7.38(1H, t), 7.55(2H, d), 7.61(2H, q), 7.66(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1625, 1490, 1400, 1260, 1135, 1010, 810 cm^{-1}; ms *m/z* 388(M$^+$), 345, 331, 274.

2-Fluoro-4''-hexoxy-4-pentylterphenyl **(111)**

Quantities: compound **109** (1.10 g, 3.43 mmol), compound **86** (1.10 g, 4.75 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2217 g, 0.19 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 1.02 g (71%); transitions (°C) K 115.0 S_C 131.5 N 166.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.04(2H, m), 7.38(1H, t), 7.57(2H, d), 7.63(4H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1605, 1510, 1490, 1470, 1400, 1290, 1250, 1210, 1180, 820 cm^{-1}; ms *m/z* 418(M$^+$), 400, 376, 361, 347, 334, 277.

2-Fluoro-4''-octoxy-4-pentylterphenyl **(112)**

Quantities: compound **109** (1.10 g, 3.43 mmol), compound **87** (1.17 g, 4.68 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2610 g, 0.23 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction

(bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 0.90 g (59%); transitions (°C) K 102.0 (S_I 99.5) S_C 137.5 N 160.0 I; ^{1}H nmr ($CDCl_3$) δ 0.85(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.04(2H, m), 7.38(1H, t), 7.57(2H, d), 7.63(4H, d); ir (KCl)ν_{max} 2960, 2940, 2880, 1610, 1495, 1400, 1290, 1250, 1210, 1185, 1130, 815 cm^{-1}; ms *m/z* 446(M^+), 418, 389, 347, 334, 277.

1-Bromo-3-fluoro-4-pent-1-ynylbenzene **(114)**

Quantities: pent-1-yne (5.00 g, 0.074 mol), n-butyllithium (7.40 ml, 10.0M in hexane, 0.074 mol), zinc chloride 10.10 g, 0.074 mol), compound **113** (20.00 g, 0.066 mol), tetrakis(triphenylphosphine)palladium(0) (2.31 g, 2.0 mmol).

The experimental procedure was as described for the preparation of compound **21**.

Yield 14.04 g (79%); bp 128-132 °C at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 1.05(3H, t), 1.65(2H, sext), 2.40(2H, t), 7.18-7.27(3H, m); ir (film) ν_{max} 2960, 2940, 2880, 2250, 1605, 1565, 1490, 1410, 1220, 1125, 1075, 870, 805 cm^{-1}; ms *m/z* 242(M^+), 240(M^+), 213, 211.

1-Bromo-3-fluoro-4-pentylbenzene **(115)**

A solution of compound **114** (9.95 g, 0.041 mol) in ethanol (180 ml) was hydrogenated over platinum(IV) oxide (0.45 g) at room temperature and atmospheric pressure for 5 h (glc analysis revealed a complete reaction). The catalyst was filtered off, the solvent was removed *in vacuo* and the residue was distilled to yield a red liquid.

Yield 9.52 g (95%); bp 122-124 at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.55(2H, quint), 2.60(2H, t), 7.04(1H, t), 7.17(2H, m); ir (film) ν_{max} 2960, 2940, 2860, 1610, 1580, 1490, 1410, 1270, 1225, 1135, 1070, 880, 860, 820 cm^{-1}; ms *m/z* 246(M^+), 244(M^+), 189, 187.

3-Fluoro-4-pentylphenylboronic acid (**116**)

Quantities: compound **115** (9.00 g, 0.037 mol), magnesium (1.00 g, 0.041 mol), tri-isopropyl borate (14.10 g, 0.075 mol).

The experimental procedure was as described for the preparation of compound **86**.

Yield 7.50 g (97%); ^{1}H nmr (CDCl$_3$) δ 0.85(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.30(1H, t), 7.76(1H, d), 7.86(1H, d) no obvious OH absorption; ir (KCl) ν_{max} 3700-3100, 2960, 2940, 2860, 1415, 1400-1300, 1100, 1040, 895, 675 cm^{-1}; ms *m/z* 234, 229, 221, 207, 193, 177, 165, 161, 149, 135.

3-Fluoro-4,4''-dipentylterphenyl (**119**)

Quantities: compound **95** (1.56 g, 5.15 mmol), compound **116** (1.30 g, 6.19 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2120 g, 0.18 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (5:1) to yield colourless crystals.

Yield 1.54 g (77%); transitions (°C) K ? S_G 156.5 S_A 185.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, t), 1.35(8H, m), 1.65(4H, m), 2.65(4H, 2xt), 7.25-7.31(4H, m), 7.34(1H, q), 7.56(2H, d), 7.63(2H, d), 7.68(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1575, 1495, 1400, 1140, 1010, 910, 880, 810 cm^{-1}; ms *m/z* 388(M$^+$), 331, 274.

3-Fluoro-4''-hexoxy-4-pentylterphenyl (**120**)

Quantities: compound **117** (1.60 g, 4.80 mmol), compound **116** (1.21 g, 5.76 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1979 g, 0.17 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised

from ethanol-ethyl acetate (1:3) to yield colourless crystals.

Yield 1.57 g (84%); transitions (°C) K ? S_G 176.0 S_A 210.0 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.25(1H, t), 7.29(1H, q), 7.34(1H, q), 7.57(2H, d), 7.62(4H, s); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1495, 1405, 1290, 1255, 1185, 1040, 880, 815 cm^{-1}; ms *m/z* 418(M^+), 361, 334, 277.

3-Fluoro-4''-octoxy-4-pentylterphenyl **(121)**

Quantities: compound **118** (1.62 g, 4.49 mmol), compound **116** (1.15 g, 5.48 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2167 g, 0.19 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (1:5) to yield colourless crystals.

Yield 1.76 g (88%); transitions (°C) K ? S_G 170.5 S_C 176.5 S_A 202.5 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.24(1H, t), 7.29(1H, q), 7.34(1H, q), 7.56(2H, d), 7.61(4H, s); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1495, 1400, 1290, 1260, 1185, 1035, 1005, 815 cm^{-1}; ms *m/z* 446(M^+), 389, 334, 277.

4-Bromo-2,5-difluoroaniline **(123)**

N-Bromosuccinimide (42.0 g, 0.24 mol) was added in small quantities over 1.5 h to a stirred, cooled (-10 to 0 °C) solution of compound **122** (31.0 g, 0.24 mol) in dry dichloromethane (180 ml) under dry nitrogen. The mixture was stirred at 0 °C for 2 h (glc analysis revealed a complete reaction), and the red solution was washed with a large amount of water (twice) and dried ($MgSO_4$). The solvent was removed *in vacuo* to afford a red solid.

Yield 47.4 g (95%); mp 74-75 °C; ^{1}H nmr ($CDCl_3$) δ 3.80(2H, s), 6.55(1H, q), 7.10(1H, q); ir (KCl) ν_{max} 3415, 3340, 1630, 1500, 1420, 1230, 1190, 1170, 870, 800, 740 cm^{-1}; ms *m/z* 209(M^+), 207(M^+), 127, 108, 101.

4-Bromo-2,5-difluorobiphenyl (**124**)

A solution of compound **123** (47.4 g, 0.23 mol) in dry benzene (200 ml) was added dropwise over 1.5 h to a stirred, cooled (0 °C) solution of isopentyl nitrite (33.6 g, 0.29 mol) in dry benzene (200 ml). The mixture was heated under reflux for 1.5 h and cooled. Ether was added and the organic phase was washed with water, aqueous sodium hydrogen carbonate, 10% hydrochloric acid and water, and dried ($MgSO_4$). The solvent was removed *in vacuo* and the crude product was steam distilled to give a brown-black solid. This was further purified by column chromatography (silica gel / dichloromethane) to give a dark brown low-melting solid.

Yield 13.20 g (22%); ^{1}H nmr ($CDCl_3$) unresolved multiplet at δ 7.00-7.80; ir (KCl) ν_{max} 3100, 2920, 1610, 1480, 1390, 1340, 1270, 1180, 880, 850, 790, 600 cm^{-1}; ms *m/z* 298, 283, 270(M^+), 268(M^+), 201, 188, 168.

4-Bromo-2,5-difluoro-4'-pentanoylbiphenyl (**125**)

Aluminium chloride (25.40 g, 0.190 mol) was ground and added to a stirred, cooled (0 °C) solution of pentanoyl chloride (34.9 g, 0.29 mol) in dry dichloromethane (120 ml). A solution of compound **124** (13.20 g, 0.049 mol) in dry dichloromethane (120 ml) was added dropwise over 2 h at 0 °C. The mixture was stirred at room temperature for 48 h and poured onto crushed ice / 36% hydrochloric acid. The separated aqueous phase was washed with dichloromethane (twice); the combined organic layers were washed with water, aqueous sodium hydrogen carbonate and water, and dried ($MgSO_4$). The solvent was removed *in vacuo* to afford a dark brown oil which was distilled under reduced pressure (0.1 mmHg, temperature not recorded) and was further purified by column chromatography (silica gel / dichloromethane) to give a low-melting brown solid.

Yield 8.00 g (46%); ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.40(2H, m), 1.70(2H, m), 3.00(2H, t), 7.25(1H, q), 7.40(1H, q), 7.60(2H, q), 8.00(2H, q); ir (KCl) ν_{max} 2900, 1680, 1610, 1480, 1390, 1180, 860, 780 cm^{-1}; ms *m/z* 310, 297, 188.

4-Bromo-2,5-difluoro-4'-pentylbiphenyl (**126**)

Triethylsilane (7.00 g, 0.06 mol) was added dropwise over 2 h to a stirred, cooled (0 °C) solution of compound **125** (8.00 g, 0.023 mol) in trifluoroacetic acid (40 ml). The reaction mixture was stirred at room temperature overnight and poured into aqueous sodium hydrogen carbonate. The product was extracted into ether (twice) and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was distilled to give a red oil.

Yield 5.50 g (70%); bp (short path), 110-120 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.80(3H, t), 1.30(4H, m), 1.60(2H, m), 2.70(2H, t), 7.00-7.40(6H, m); ms *m/z* 340(M^+), 338(M^+), 283, 201.

2',5'-Difluoro-4,4''-dipentylterphenyl (**127**)

Quantities: compound **126** (1.25 g, 3.69 mmol), compound **94** (0.8604 g, 4.48 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1404 g, 0.122 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.56 g (37%); transitions (°C) K 63.0 N 85.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, t), 1.40(8H, m), 1.65(4H, quint), 2.65(4H, t), 7.20 (2H, q), 7.25(4H, d), 7.50(4H, d); ir (KCl) ν_{max} 2960, 2920, 2860, 1630, 1480, 1390, 1270, 1170, 1120, 1020, 880 cm^{-1}; ms *m/z* 406(M^+), 349, 292, 203.

2',5'-Difluoro-4-hexoxy-4''-pentylterphenyl (**128**)

Quantities: compound **126** (1.25 g, 3.69 mmol), compound **86** (0.9806 g, 4.42 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1392 g, 0.121 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.72 g (45%); transitions (°C) K 51.0 N 117.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.18(1H, q), 7.23(1H, q), 7.27(2H, d), 7.48(2H, q), 7.53(2H, q); ir (KCl) ν_{max} 2960, 2940, 2870, 2860, 1610, 1530, 1490, 1390, 1260, 1170, 1030, 890 cm^{-1}; ms *m/z* 436(M$^+$), 397, 379, 366, 352, 295, 282.

2,6-Difluoro-4-pentylphenylboronic acid (**129**)

n-Butyllithium (2.70 ml, 10.4M in hexane, 0.028 mol) was added dropwise to a stirred, cooled (-78 °C) solution of compound **32** (5.00 g, 0.027 mol) in dry THF (60 ml) under dry nitrogen. The reaction mixture was maintained under these conditions for 2.5 h and then a previously cooled solution of tri-isopropyl borate (10.22 g, 0.054 mol) in dry THF (50 ml) was added dropwise at -78 °C. The reaction mixture was allowed to warm to room temperature overnight and then stirred for 1 h with 10% hydrochloric acid (30 ml). The product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a colourless solid.

Yield 7.00 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.60(2H, m), 2.60(2H, t), 5.45(2H, t), 6.65(2H, d); ir (KCl) ν_{max} 3350, 2960, 2940, 2850, 1640, 1555, 1440, 1330, 1200, 1130, 1010, 1000, 860, 810 cm^{-1}; ms *m/z* 228(M$^+$), 211, 200, 185, 171, 153, 143, 128, 108.

2,6-Difluoro-4,4''-dipentylterphenyl (**130**)

Quantities: compound **95** (1.40 g, 4.62 mmol), compound **129** (1.37 g, 6.00 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2614 g, 0.226 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a colourless liquid which contained a solid. The solid was filtered off and washed with petroleum fraction (bp 40-60 °C). The solvent was removed from the filtrate and washings *in vacuo* to give a colourless liquid; two impurities were removed using a Kugelrohr distillation apparatus (0.1 mmHg) to leave a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.19 g (10%); transitions (°C) K 50.0 N 82.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.65(4H, m), 2.60(4H, 2xt), 6.80(2H, d), 7.25(2H, d), 7.50(2H, d), 7.55(2H, d), 7.65(2H, d); ir (KCl) ν_{max} 2980, 2950, 2880, 1640, 1580, 1480, 1430, 1400, 1200, 1020, 1010, 860 cm^{-1}; ms *m/z* 406(M^+), 349, 292.

2,6-Difluoro-4''-hexoxy-4-pentylterphenyl **(131)**

Quantities: compound **117** (1.30 g, 3.90 mmol), compound **129** (1.10 g, 4.82 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1579 g, 0.137 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [basic alumina / petroleum fraction (bp 40-60 °C) with the gradual addition of dichloromethane] to give a colourless solid which was recrystallised from ethanol to give colourless crystals.

Yield 0.20 g (20%); transitions (°C) K 61.0 N 122.5 I; ^{1}H nmr ($CDCl_3$) δ 0.95(6H, 2xt), 1.35(8H, m), 1.50(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.60(2H, t), 4.00(2H, t), 6.80(2H, d), 6.95(2H, d), 7.50(2H, d), 7.55(2H, d), 7.65(2H, d); ir (KCl) ν_{max} 2950, 2860, 1640, 1610, 1580, 1510, 1490, 1290, 1250, 1210, 1020, 820 cm^{-1}; ms *m/z* 436(M^+), 352, 295.

3,5-Difluoro-4'-hexoxybiphenyl **(132)**

Quantities: compound **29** (5.00 g, 0.026 mol), compound **86** (7.50 g, 0.03 mol), tetrakis(triphenylphosphine)palladium(0) (1.50 g, 1.30 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / dichloromethane] to yield a colourless solid.

Yield 7.40 g (98%); mp 42-43 °C; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.45(2H, quint), 1.80(2H, quint), 3.95(2H, t), 6.70(1H, 3xt), 6.95(2H, d), 7.05(2H, d), 7.45(2H, d); ir (KCl) ν_{max} 2960, 2920, 2880, 2860, 1630, 1610, 1600, 1580, 1530, 1470, 1450, 1290, 1260, 1210, 1110, 990, 840, 830, 810, 670, 630 cm^{-1}; ms *m/z* 290(M$^+$), 206, 178, 151.

3,5-Difluoro-4'-hexoxybiphenyl-4-ylboronic acid **(133)**

Quantities: compound **132** (7.30 g, 0.025 mol), n-butyllithium (10.0 ml, 2.5M in hexane, 0.025 mol), tri-isopropyl borate (9.40 g, 0.050 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 8.35 g (100%); ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(4H, m), 1.45(2H, quint), 1.80(2H, quint), 3.95(2H, t), 6.95(2H, d), 7.05(2H, d), 7.50(2H, d), no obvious OH absorption; ir (KCl) ν_{max} 3700-3100, 2950, 2860, 1630, 1610, 1550, 1530, 1440, 1400, 1290, 1250, 1180, 1120, 1060, 1020, 830 cm^{-1}; ms *m/z* 367, 354, 344, 330, 318, 306, 290, 282, 270, 254, 246, 233.

Attempted preparation of 2',6'-difluoro-4''-hexoxy-4-pentylterphenyl **(134)**

Quantities: compound **91** (1.30 g, 5.73 mmol), compound **133** (2.40 g, 7.18 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2491 g, 0.21 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was identified as compound **132**.

Yield 2.05 g (98%); mp 42-43 °C; ^{1}H nmr, ir and ms data were as for compound **132**.

2-Fluoro-4-hexoxyphenylboronic acid (**135**)

Quantities: compound **105** (9.00 g, 0.033 mol), n-butyllithium (3.30 ml, 10.0M in hexane, 0.033 mol), tri-isopropyl borate (11.28 g, 0.060 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 7.80 g (99%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.45(2H, quint),1.80(2H, quint), 3.95(2H, t), 5.00(<2H, d), 6.55(1H, q), 6.75(1H, q), 7.70(1H, t); ir (KCl) ν_{max} 3350, 2950, 2880, 1630, 1570, 1430, 1380, 1340, 1320, 1270, 1160, 1010, 1000 cm^{-1}; ms *m/z* 240(M^+), 233, 225, 128, 112.

2,2"-Difluoro-4-hexoxy-4"-pentylterphenyl (**136**)

Quantities: compound **109** (1.45 g, 4.50 mmol), compound **135** (1.30 g, 5.42 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1691 g, 0.146 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane 3:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.31 g (16%); transitions (°C) K 45.0 N 131.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.40(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.72(1H, q), 6.78(1H, q), 6.99(1H, q), 7.04(1H, q), 7.38(2H, 2xt), 7.60(4H, s); ir (KCl) ν_{max} 2960, 2940, 2860, 1620, 1490, 1390, 1310, 1250, 1230, 1160, 1020 cm^{-1}; ms *m/z* 436(M^+), 352, 295, 266, 185.

2-Fluoro-4-pentylbiphenyl-4'-ylboronic acid (**137**)

Quantities: compound **109** (9.90 g, 0.031 mol), magnesium (0.8710 g, 0.036 mol), tri-isopropyl borate (11.66 g, 0.062 mol).

The experimental procedure was as described for the preparation of compound **86**.

Yield 8.85 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.60(2H, t), 7.00(2H, d), 7.35(2H, m), 7.50(1H, d), 7.60-7.80(2H, m), no obvious OH absorption; ir (KCl) ν_{max} 3600-3200, 2980, 2960, 2860, 1640, 1620, 1580, 1535, 1405, 1390-1320, 1140, 840 cm^{-1}; ms *m/z* 368, 356, 320, 311, 299, 286(M$^+$), 285, 272, 262, 258, 252, 237.

2,2''-Difluoro-4-octoxy-4''-pentylterphenyl (138)

Quantities: compound **106** (1.45 g, 4.79 mmol), compound **137** (1.75 g, 6.12 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2979 g, 0.26 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 1.57 g (55%); transitions (°C) K 42.5 N 121.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.72(1H, q), 6.78(1H, q), 6.99(1H, q), 7.04(1H, q), 7.38(2H, 2xt), 7.60(4H, s); ir (KCl) ν_{max} 2940, 2860, 1630, 1495, 1480, 1405, 1325, 1315, 1170 cm^{-1}; ms *m/z* 464(M$^+$), 351, 335, 320, 306, 294.

2,3''-Difluoro-4''-hexoxy-4-pentylterphenyl (139)

Quantities: compound **100** (1.35 g, 4.91 mmol), compound **137** (1.77 g, 6.19 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2991 g, 0.26 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.10 g (51%); transitions (°C) K 96.0 S_C 105.5 N 139.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.05(2H, t), 7.00(3H, m), 7.35(3H, m), 7.60(4H, s); ir (KCl) ν_{max} 2970, 2940, 2880, 1625, 1590, 1520, 1470, 1405, 1305, 1140, 810 cm^{-1}; ms *m/z* 436(M^+), 379, 352, 295.

2,3''-Difluoro-4''-octoxy-4-pentylterphenyl **(140)**

Quantities: compound **101** (0.80 g, 2.64 mmol), compound **137** (1.00 g, 3.50 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1621 g, 0.14 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (5:1) to yield colourless crystals.

Yield 0.96 g (78%); transitions (°C) K 75.5 S_C 107.0 N 132.0 I; ^1H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.50(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.05(2H, t), 7.00(3H, m), 7.35(3H, m), 7.60(4H, s); ir (KCl) ν_{max} 2960, 2940, 2860, 1620, 1520, 1500, 1570, 1400, 1300, 1275, 1245, 1190, 1140, 870, 805 cm^{-1}; ms *m/z* 464(M^+), 407, 352.

2,3-Difluorophenylboronic acid **(142)**

Quantities: compound **141** (7.50 g, 0.066 mol), n-butyllithium (6.60 ml, 10.0M in hexane, 0.066 mol), tri-isopropyl borate (24.82 g, 0.132 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 9.80 g (94%); mp 234-237 °C; ^1H nmr ($CDCl_3$) δ 7.10(q), 7.15(t), 7.50(s, broad), 7.65(t); ir (KCl) ν_{max} 3700-3000, 1625, 1470, 1360, 1270, 1045, 905 cm^{-1}; ms *m/z* 158(M^+), 140, 125, 114.

2,3-Difluoro-4'-pentylbiphenyl **(143)**

Quantities: compound **91** (3.80 g, 0.017 mol), compound **142** (3.50 g, 0.022 mol), tetrakis(triphenylphosphine)palladium(0) (0.6510 g, 0.56 mmol).

The experimental procedure was as described for the preparation of compound **97**.

The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to yield a colourless liquid.

Yield 4.30 g (99%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.60(2H, t), 7.05-7.15(3H, m), 7.25(2H, d), 7.45(2H, q); ir (film) ν_{max} 2960, 2940, 2860, 1480, 1265, 1100, 895, 780 cm^{-1}; ms *m/z* 260(M$^+$), 203.

2,3-Difluoro-4'-nonylbiphenyl **(144)**

Quantities: compound **93** (3.50 g, 0.012 mol), compound **142** (2.35 g, 0.015 mol), tetrakis(triphenylphosphine)palladium(0) (0.72 g, 0.62 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless liquid.

Yield 2.93 g (77%); ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.25(12H, s), 1.60(2H, t), 2.60(2H, t), 7.06-7.18(3H, m), 7.27(2H, d), 7.46(2H, q); ir (film) ν_{max} 2960, 2860, 1630, 1595, 1520, 1485, 1410, 1315, 1265, 1225, 1100, 900, 780 cm^{-1}; ms *m/z* 316(M$^+$), 203, 183.

2,3-Difluoro-4'-pentylbiphenyl-4-ylboronic acid **(145)**

Quantities: compound **143** (4.00 g, 0.015 mol), n-butyllithium (1.50 ml, 10.0M in hexane, 0.015 mol), tri-isopropyl borate (5.70 g, 0.030 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 4.50 g (99%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.65(2H, t), 2.65(2H, t), 5.20(2H, d), 7.25-7.35(3H, m), 7.50(2H, q), 7.60(1H, sext); ir (KCl) ν_{max} 3600-3000, 2960, 2940, 2860, 1625, 1520, 1450, 1355, 1220, 915 cm^{-1}; ms *m/z* 304 (M$^+$), 260, 203.

2,3-Difluoro-4'-nonylbiphenyl-4-ylboronic acid (**146**)

Quantities: compound **144** (2.71 g, 8.58 mmol), n-butyllithium (3.44 ml, 2.5M in hexane, 8.60 mmol), tri-isopropyl borate (3.30 g, 0.018 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 3.10 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(12H, m), 1.60(2H, quint), 2.65(2H, t), 7.20(2H, m), 7.27(2H, d), 7.47(2H, q), no obvious OH absorption; ir (KCl) ν_{max} 3700-3100, 2960, 2940, 2860, 1630, 1525, 1455, 1420-1300, 1225, 1165, 1100, 1035, 915, 895, 830, 810, 755 cm^{-1}; ms *m/z* 332, 316, 307, 280, 203.

2',3'-Difluoro-4-hexoxy-4''-pentylterphenyl (**147**)

Quantities: compound **84** (1.30 g, 5.06 mmol), compound **145** (2.00 g, 6.58 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3121 g, 0.27 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 1.10 g (50%); transitions (°C) K 54.0 S_C 67.0 N 149.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.22(2H, m), 7.30(2H, d), 7.50(2H, q), 7.52(2H, q); ir (KCl) ν_{max} 2960, 2930, 2855, 1605, 1480, 1460, 1405, 1250, 1105 cm^{-1}; ms *m/z* 436(M$^+$), 379, 352, 295.

2',3'-Difluoro-4-octoxy-4''-pentylterphenyl (**148**)

Quantities: compound **85** (1.40 g, 4.91 mmol), compound **145** (1.90 g, 6.25 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3102 g, 0.27 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction

(bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (4:1) to yield colourless crystals.

Yield 1.75 g (77%); transitions (°C) K 48.5 S_C 95.0 N 141.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.22(2H, m), 7.28(2H, d), 7.50(2H, q), 7.53(2H, q); ir (KCl) ν_{max} 2980, 2940, 2880, 1625, 1540, 1500, 1470, 1420, 1260, 1190, 1115, 915, 810 cm^{-1}; ms *m/z* 464(M$^+$), 407, 394, 352.

<u>2',3'-Difluoro-4,4''-dipentylterphenyl</u> (149)

<u>Quantities</u>: compound **91** (1.30 g, 5.73 mmol), compound **145** (2.10 g, 6.90 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3267 g, 6.90 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to yield a colourless solid which was recrystallised from ethanol to give colourless crystals.

Yield 1.27 g (55%); transitions (°C) K 60.0 N 120.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.65(4H, quint), 2.65(4H, t), 7.22(2H, m), 7.28(4H, d), 7.50(4H, d); ir (KCl) ν_{max} 2960, 2930, 2855, 1480, 1460, 1405, 1105 cm^{-1}; ms *m/z* 406(M$^+$), 349.

<u>2',3'-Difluoro-4-heptyl-4''-pentylterphenyl</u> (150)

<u>Quantities</u>: compound **92** (1.27 g, 4.98 mmol), compound **145** (1.82, 5.99 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3069 g, 0.266 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 20:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.86 g (40%); transitions (°C) K 36.5 (S_C 24.0) N 111.5 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.65(4H, quint), 2.65(4H, t), 7.24(2H, m), 7.28(4H, d), 7.52(4H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1410, 1205, 1020, 910, 895, 795 cm^{-1}; ms *m/z* 434(M$^+$), 377, 363, 349, 292.

2',3'-Difluoro-4-nonyl-4''-pentylterphenyl (**151**)

Quantities: compound **93** (3.10 g, 0.011 mol), compound **145** (4.25 g, 0.014 mol), tetrakis(triphenylphosphine)palladium(0) (0.5118 g, 0.44 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol (+ 5 drops of ethyl acetate) to yield colourless crystals.

Yield 1.86 g (37 %); transitions (°C) K 42.5 S_C 66.0 N 110.0 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(16H, m), 1.65(4H, quint), 2.65(4H, t), 7.24(2H, m), 7.28(4H, d), 7.50(4H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1410, 1320, 1205, 1105, 910, 895, 800 cm^{-1}; ms *m/z* 462(M$^+$), 405, 349, 292.

2',3'-Difluoro-4-heptyl-4''-nonylterphenyl (**152**)

Quantities: compound **92** (1.00 g, 3.92 mmol), compound **146** (1.65 g, 4.58 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2398 g, 0.208 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 0.71 g (37%); transitions (°C) K 49.0 S_C 77.0 S_A 93.0 N 108.5 I;

^{1}H nmr ($CDCl_3$) δ 0.85(6H, 2xt), 1.30(20H, m), 1.65(4H, quint), 2.65(4H, t), 7.24(2H, m), 7.28(4H, d), 7.52(4H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1410, 1205, 1105, 1020, 910, 895, 800 cm^{-1}; ms *m/z* 490(M$^+$), 446, 405, 392, 377, 316, 292.

2,3-Difluorophenol (**153**)

10% Hydrogen peroxide (30 ml, 0.088 mol) was added dropwise to a stirred refluxing solution of compound **142** (4.40 g, 0.028 mol) in ether (30 ml). The stirred mixture was heated under reflux for 2.5 h and cooled. The ether layer was separated and the aqueous layer was washed with ether. The combined ethereal layers were washed with 10% sodium hydroxide and the separated aqueous layer was acidified with 36% hydrochloric acid. The product was extracted into ether (twice), and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give an off white solid.

Yield 2.90 g (80%); mp 34-36 °C; ^1H nmr ($CDCl_3$) δ 5.35(1H, s), 6.65-6.80(2H, m), 6.95(1H, q); ir (KCl) 3700-3000, 1630, 1540, 1515, 1490, 1480, 1350, 1310, 1250, 1190, 1020 cm^{-1}; ms *m/z* 130(M^+), 110, 101.

1,2-Difluoro-3-hexoxybenzene (**154**)

Quantities: compound **153** (7.00 g, 0.054 mol), 1-bromohexane (10.72 g, 0.065 mol), potassium carbonate (17.40 g, 0.126 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 11.10 g (96%); bp 122 °C at 15 mmHg; ^1H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.40(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.75(2H, m), 6.95(1H, m); ir (KCl) ν_{max} 2980, 2940, 2880, 1635, 1525, 1495, 1325, 1300, 1265, 1090 cm^{-1}; ms *m/z* 214(M^+), 130.

1,2-Difluoro-3-octoxybenzene (**155**)

Quantities: compound **153** (7.00 g, 0.054 mol), 1-bromo-octane (12.55 g, 0.065 mol), potassium carbonate (17.40 g, 0.126 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 8.90 g (68%); bp 150 °C at 15 mmHg; ^1H nmr ($CDCl_3$) δ 0.85(3H, t), 1.25(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.75(2H, m), 6.95(1H, m); ir (KCl) ν_{max} 2950, 2880, 1630, 1525, 1490, 1485, 1325, 1300, 1265, 1090 cm^{-1}; ms *m/z* 242(M$^+$), 171, 156, 130.

2,3-Difluoro-4-hexoxyphenylboronic acid **(156)**

Quantities: compound **154** (10.00 g, 0.047 mol), n-butyllithium (4.70 ml, 10.0M in hexane, 0.047 mol), tri-isopropyl borate (17.70 g, 0.094 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 12.10 g (100%); ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(4H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.70(1H, t), 7.55(1H, t), no obvious OH absorption; ir (KCl) ν_{max} 3650-3100, 2960, 2940, 2860, 1630, 1525, 1470, 1360, 1310, 1225, 1035 cm^{-1}; ms *m/z* 258(M$^+$), 174.

2,3-Difluoro-4-octoxyphenylboronic acid **(157)**

Quantities: compound **155** (7.50 g, 0.031 mol), n-butyllithium (3.10 ml, 10.0M in hexane, 0.031 mol), tri-isopropyl borate (11.66 g, 0.062 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 9.00 g (100%); ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.30(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.05(2H, t), 6.80(1H, t), 7.80(1H, t), no obvious OH absorption; ir (KCl) ν_{max} 3600-3100, 2980, 2940, 2880, 1635, 1530, 1475, 1365, 1315, 1230, 1090, 1035 cm^{-1}; ms *m/z* 286(M$^+$), 271, 258, 241.

2,3-Difluoro-4-hexoxy-4''-pentylterphenyl **(159)**

Quantities: compound **95** (1.40 g, 4.62 mmol), compound **156** (1.50 g, 5.81 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2868 g, 0.248 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction

(bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.65 g (82%); transitions (°C) K 97.5 S_C 145.5 N 166.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, t), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.05(2H, t), 6.80(1H, sext), 7.15(1H, sext), 7.25(2H, d), 7.54(2H, d), 7.57(2H, q), 7.65(2H, d); ir (KCl) ν_{max} 2990, 2960, 2880, 1645, 1525, 1505, 1475, 1405, 1310, 1205, 1120, 1090, 805 cm^{-1}; ms *m/z* 436(M^+), 351, 334, 322, 306, 294.

2,3-Difluoro-4-octoxy-4''-pentylterphenyl **(160)**

Quantities: compound **95** (1.54 g, 5.08 mmol), compound **157** (1.75 g, 6.12 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3090 g, 0.268 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (4:1) to yield colourless crystals.

Yield 1.97 g (84%); transitions (°C) K 93.5 S_C 144.0 S_A 148.0 N 159.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, t), 2.65(2H, t), 4.05(2H, t), 6.80(1H, sext), 7.15(1H, sext), 7.25(2H, d), 7.54(2H, d), 7.57(2H, q), 7.65(2H, d); ir (KCl) ν_{max} 2980, 2940, 2880, 1645, 1525, 1505, 1475, 1405, 1310, 1090 cm^{-1}; ms *m/z* 464(M^+), 351, 321, 307, 294.

2,3-Difluoro-4-octoxy-4''-heptylterphenyl **(161)**

Quantities: compound **158** (1.54 g, 4.65 mmol), compound **157** (1.80 g, 6.29 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2717 g, 0.23 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised

from ethanol-ethyl acetate (4:1) to yield colourless crystals.

Yield 1.72 g (75%); transitions (°C) K 89.5 S_C 148.0 S_A 151.5 N 154.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(16H, m), 1.45(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.05(2H, t), 6.81(1H, sext), 7.13(1H, sext), 7.27(2H, d), 7.54(2H, d), 7.57(2H, q), 7.65(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1635, 1505, 1470, 1400, 1305, 1200, 1210, 1085, 900, 805 cm^{-1}; ms *m/z* 492(M^+), 435, 408, 380, 295.

1-(2,3-Difluorophenyl)pentan-1-ol **(162)**

n-Butyllithium (10.50 ml, 10.0M in hexane, 0.105 mol) was added dropwise to a stirred, cooled (-78 °C) solution of compound **141** (12.00 g, 0.105 mol) in dry THF (80 ml) under dry nitrogen. The mixture was maintained under these conditions for 2.5 h and a solution of pentanal (9.03 g, 0.105 mol) in dry THF (50 ml) was added dropwise at -78 °C. The mixture was allowed to warm slowly to room temperature overnight. Aqueous ammonium chloride was added and the product was extracted into ether (twice); the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was distilled to yield a colourless oil.

Yield 18.25 g (87%); bp 182-184 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(4H, m), 1.75(2H, m), 2.80(1H, s), 4.95(1H, t), 7.05(2H, m), 7.18(1H, m); ir (film) ν_{max} 3500-3100, 2960, 2940, 2860, 1630, 1600, 1485, 1275, 1205, 830 cm^{-1}; ms *m/z* 200(M^+), 149, 143, 127, 115.

1-(2,3-Difluorophenyl)heptan-1-ol **(163)**

Quantities: compound **141** (12.00 g, 0.105 mol), n-butyllithium (42.00 ml, 2.5M in hexane, 0.105 mol), heptanal (11.97 g, 0.105 mol).

The experimental procedure was as described for the preparation of compound **162**.

Yield 20.70 g (86%), bp 106-108 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(8H, m), 1.75(2H, m), 2.45(1H, s), 5.00(1H, t), 7.02-7.08(2H, m), 7.16-7.22(1H, m); ir (film) ν_{max} 3600-3100, 2960, 2940, 2860, 1630, 1600, 1485, 1280, 1205, 1065, 935, 835, 790, 730 cm^{-1}; ms *m/z* 228(M$^+$).

1-(2,3-Difluorophenyl)nonan-1-ol **(164)**.

Quantities: compound **141** (12.00 g, 0.105 mol), n-butyllithium (10.50 ml, 10.0M in hexane, 0.105 mol), nonanal (14.91 g, 0.105 mol).

The experimental procedure was as described for the preparation of compound **162**.

Yield 19.61 g (73%); bp 118-122 °C at 0.1 mmHg; ^{1}H nmr (CDCl$_3$) δ 0.85(3H, t), 1.25(12H, m), 1.75(2H, m), 2.95(1H, s), 5.00(1H, t), 7.05(2H, m), 7.18(1H, m); ir (film) ν_{max} 3600-3100, 2940, 2860, 1630, 1600, 1485, 1275, 1205, 1060, 825, 785 cm^{-1}; ms *m/z* 256(M$^+$), 238, 216, 203, 142.

1,2-Difluoro-3-pentylbenzene **(168)**

Phosphorus(V) oxide (34.1 g, 0.24 mol) was added to a stirred solution of compound **162** (16.00 g, 0.08 mol) in pentane (100 ml). The mixture was stirred at room temperature overnight (glc analysis revealed a complete reaction) and the mixture was filtered. 5% Palladium-on-charcoal (1.85 g) was added to the filtrate and the stirred mixture was hydrogenated for 4 h at room temperature and atmospheric pressure (glc analysis revealed a complete reaction). The palladium-on-charcoal was filtered off, the pentane was distilled off and the product was distilled to yield a colourless liquid.

Yield 10.45 g (71%); bp 206-208 °C; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.35(4H, m), 1.60(2H, quint), 2.65(2H, t), 6.90-7.00(3H, m); ir (film) ν_{max} 2960, 2940, 2860, 1630, 1600, 1490, 1285, 1210, 1110, 1060, 995, 835, 780, 730 cm^{-1}; ms *m/z* 184(M$^+$), 143, 127, 115, 101.

1,2-Difluoro-3-heptylbenzene **(169)**.

Quantities: compound **163** (19.70 g, 0.086 mol), phosphorus(V) oxide (37.0 g, 0.26 mol), 5% Pd/C (2.00 g).

The experimental procedure was as described for the preparation of compound **168**.

Yield 10.72 g (59%); bp 124-126 °C at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(8H, m), 1.60(2H, quint), 2.65(2H, t), 6.92-7.00(3H, m); ir (film) ν_{max} 2960, 2940, 2860, 1630, 1600, 1490, 1285, 1210, 980, 825, 780, 730 cm^{-1}; ms *m/z* 212(M^+), 169, 153, 143, 128.

1,2-Difluoro-3-nonylbenzene (170)

Quantities: compound **164** (18.50 g, 0.072 mol), phosphorus(V) oxide (32.0 g, 0.23 mol), 5% Pd/C (2.00 g).

The experimental procedure was as described for the preparation of compound **168**.

Yield 11.16 g (65%); bp 146-148 °C at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.60(12H, m), 1.60(2H, quint), 2.65(2H, t), 6.92-7.00(3H, m); ir (film) ν_{max} 2980, 2960, 2860, 1630, 1600, 1490, 1285, 1210, 1040, 995, 825, 780, 730 cm^{-1}; ms *m/z* 240(M^+), 197, 182.

2,3-Difluoro-4-pentylphenylboronic acid (171)

Quantities: compound **168** (9.85 g, 0.054 mol), n-butyllithium (5.40 ml, 10.0M in hexane, 0.054 mol), tri-isopropyl borate (21.00 g, 0.111 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 12.30 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.65(2H, t), 6.95(1H, m), 7.45(1H, m), no obvious OH absorption; ir (film) ν_{max} 3600-3100, 2980, 2940, 2860, 1640, 1460, 1400-1280, 1220, 1140, 1000, 960 cm^{-1}; ms *m/z* 228(M^+), 211, 205, 197, 193, 184, 171, 153, 149, 143.

2,3-Difluoro-4-heptylphenylboronic acid (**172**)

Quantities: compound **169** (9.80 g, 0.046 mol), n-butyllithium (4.60 ml, 10.0M in hexane, 0.046 mol), tri-isopropyl borate (18.0 g, 0.096 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 11.75 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.25(8H, m), 1.60(2H, quint), 2.65(2H, t), 6.96(1H, m), 7.40(1H, m), no obvious OH absorption; ir (KCl) ν_{max} 3600-3100, 2960, 2940, 2860, 1635, 1455, 1435-1250, 1220, 1135, 670 cm^{-1}; ms *m/z* 298, 270, 256(M^+), 239, 228, 220, 212, 199, 185, 171, 155, 142, 127.

2,3-Difluoro-4-nonylphenylboronic acid (**173**)

Quantities: compound **170** (10.15 g, 0.042 mol), n-butyllithium (4.20 ml, 10.0M in hexane, 0.042 mol), tri-isopropyl borate (16.00 g, 0.085 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 11.90 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(12H, m), 1.60(2H, m), 2.65(2H, t), 7.00(1H, m), 7.40(1H, t), no obvious OH apsorption; ir (KCl) ν_{max} 3600-3200, 2960, 2940, 2860, 1635, 1460, 1400-1335, 1320, 1135 cm^{-1}; ms *m/z* 284(M^+), 267, 256, 213, 199, 184, 172.

2,3-Difluoro-4,4''-dipentylterphenyl (**175**)

Quantities: compound **95** (1.60 g, 5.28 mmol), compound **171** (1.45 g, 6.36 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3767 g, 0.326 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.70g (79%); transitions (°C) K 81.0 S_C 115.5 S_A 131.5 N 142.0 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, t), 1.35(8H, m), 1.65(4H, quint), 2.65(4H, 2xt), 7.00(1H, sext), 7.15(1H, sext), 7.28(2H, d), 7.56(2H, d), 7.60(2H, q), 7.68(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1400, 900, 805 cm^{-1}; ms *m/z* 406(M$^+$), 361, 349, 337, 305, 292.

2,3-Difluoro-4''-hexoxy-4-pentylterphenyl (**176**)

Quantities: compound **117** (1.67 g, 5.02 mmol), compound **171** (1.40 g, 6.14 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3420 g, 0.296 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate to yield colourless crystals.

Yield 1.30 g (59%); transitions (°C) K 101.5 S_C 156.5 S_A 167.0 N 171.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.00(1H, sext), 7.14(1H, sext), 7.56(2H, d), 7.59(2H, q), 7.63(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1605, 1510, 1490, 1465, 1290, 1255, 1185, 1120, 900, 835, 805 cm^{-1}; ms *m/z* 464(M$^+$), 435, 420, 408, 390, 379, 366, 352.

2,3-Difluoro-4''-octoxy-4-pentylterphenyl (**177**)

Quantities: compound **118** (1.70 g, 4.71 mmol), compound **171** (1.30 g, 5.70 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3127 g, 0.271 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (3:1) to yield colourless crystals.

Yield 1.60 g (73%); transitions (°C) K 89.0 S_C 155.5 S_A 165.0 N 166.0 I. ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.98(2H, d), 7.00(1H, sext), 7.14(1H, sext), 7.57(2H, d), 7.60(2H, q), 7.64(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1510, 1490, 1400, 1290, 1255, 1185, 920, 900, 830, 810 cm^{-1}; ms *m/z* 464(M$^+$), 435, 420, 408, 390, 379, 366, 352.

2,3-Difluoro-4''-heptyl-4-pentylterphenyl (178)

Quantities: compound **158** (1.64 g, 4.95 mmol), compound **171** (1.35 g, 5.92 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3211 g, 0.278 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.52 g (71%);

transitions (°C) K 65.5 S_I 74.5 S_C 118.5 S_A 135.0 N 137.0 I.

^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.65(4H, quint), 2.65(4H, 2xt), 7.00(1H, sext), 7.15(1H, sext), 7.28(2H, d), 7.56(2H, d), 7.60(2H, q), 7.67(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1400, 1315, 1120, 895, 805 cm^{-1}; ms *m/z* 434(M$^+$), 421, 391, 377, 362, 349, 336.

2,3-Difluoro-4-heptyl-4''-pentylterphenyl (179)

Quantities: compound **95** (1.50 g, 4.95 mmol), compound **172** (1.52 g, 5.94, mmol) tetrakis(triphenylphosphine)palladium(0) (0.3421 g, 0.296 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.54 g (72%); transitions (°C) K 56.0 S_C 105.5 S_A 131.0 N 136.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.65(4H, quint), 2.65(4H, 2xt), 7.00(1H, sext), 7.15(1H, sext), 7.28(2H, d), 7.56(2H, d), 7.60(2H, q), 7.68(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1400, 1220, 1185, 1125, 900, 810 cm^{-1}; ms *m/z* 434(M$^+$), 420, 405, 390, 377, 363, 349.

2,3-Difluoro-4-nonyl-4''-propylterphenyl **(180)**

Quantities: compound **174** (1.37 g, 4.98 mmol), compound **173** (1.75 g, 6.16 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3167 g, 0.274 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.78 g (82%);

transitions (°C) K 63.0 / 80.0 S_C 84.5 S_A 117.0 N 131.5 I;

^{1}H nmr (CDCl$_3$) δ 0.85(3H, t), 0.95(3H, t), 1.30(12H, m), 1.65(4H, quint), 2.65(4H, 2xt), 7.00(1H, sext), 7.16(1H, sext), 7.28(2H, d), 7.56(2H, d), 7.60(2H, q), 7.66(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1400, 1120, 900, 805 cm^{-1}; ms *m/z* 434(M$^+$), 405, 334, 321, 305, 292.

2,3-Difluoro-4-nonyl-4''-heptylterphenyl **(181)**

Quantities: compound **158** (1.53 g, 4.62 mmol), compound **173** (1.80 g, 6.34 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2696 g, 0.23 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate to yield colourless crystals.

Yield 2.00 g (88%); transitions (°C) K 44.0 S_I 55.0 S_C 105.0 S_A 127.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(20H, m), 1.65(4H, quint), 2.65(4H, 2xt), 6.99(1H, sext), 7.15(1H, sext), 7.27(2H, d), 7.55(2H, d), 7.59(2H, q), 7.67(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1400, 1125, 1010, 900, 805 cm^{-1}; ms *m/z* 490(M$^+$), 405, 377, 292.

4-(4-Methylhexyl)phenylboronic acid (183)

Quantities: compound **182** (7.90 g, 0.031 mol), n-butyllithium (3.10 ml, 10.0M in hexane, 0.031 mol), tri-isopropyl borate (12.00 g, 0.064 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 6.80 g (100%); ^{1}H nmr (CDCl$_3$) δ 0.85(7H, m), 1.15(2H, m), 1.35(2H, m), 1.65(2H, quint), 2.65(2H, t), 7.30(2H, d), 8.10(2H, d), no obvious OH absorption; ir (film) ν_{max} 2960, 2940, 2880, 1615, 1565, 1520, 1500-1270, 1185, 1025 cm^{-1}; ms *m/z* 221, 219, 205, 192, 185, 176, 165, 149, 135, 131, 125, 107.

4-Bromo-4'-(4-methylhexyl)biphenyl (185)

Quantities: compound **184** (3.50 g, 0.012 mol), compound **183** (3.30 g, 0.015 mol), tetrakis(triphenylphosphine)palladium(0) (0.70 g, 0.61 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and heated under reflux for 1.5 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid.

Yield 3.75 g (94%); mp 78-79 °C; ^{1}H nmr (CDCl$_3$) δ 0.85(7H, m), 1.15(2H, m), 1.35(2H, quint), 1.60(2H, quint), 2.60(2H, t), 7.25(2H, d), 7.43(2H, d), 7.47(2H, d), 7.54(2H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 2860, 1485, 1465, 1390, 1380, 1080, 810 cm^{-1}; ms *m/z* 332(M$^+$), 330(M$^+$), 247, 245, 232, 198, 167, 165.

2,3-Difluoro-4''-(4-methylhexyl)-4-pentylterphenyl (186)

Quantities: compound **185** (1.15 g, 3.47 mmol), compound **171** (0.96 g, 4.21 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2117 g, 0.183 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised

from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 0.90 g (60%); transitions (°C) K 64.0 S_C 86.0 N 100.5 I;

^{1}H nmr ($CDCl_3$) δ 0.90(9H, m), 1.20(2H, sept), 1.35(7H, m), 1.65(4H, quint), 2.70(4H, 2xt), 7.00(1H, sext), 7.15(1H, sext), 7.28(2H, d), 7.56(2H, d), 7.60(2H, q), 7.67(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1490, 1465, 1400, 1315, 1220, 1185, 1120, 900, 805 cm^{-1}; ms *m/z* 434(M$^+$), 377, 362, 349.

2,3-Difluoro-4''-(4-methylhexyl)-4-octoxyterphenyl **(187)**

Quantities: compound **185** (1.49 g, 4.23 mmol), compound **157** (1.46 g, 5.10 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2618 g, 0.227 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.16 g (56%); transitions (°C) K 72.0 S_C 120.0 N 128.0 I;

^{1}H nmr ($CDCl_3$) δ 0.85(9H, m), 1.15(2H, sept), 1.30(11H, m), 1.45(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.05(2H, t), 6.81(1H, sext), 7.14(1H, sext), 7.28(2H, d), 7.54(2H, d), 7.57(2H, q), 7.66(2H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 1630, 1500, 1470, 1300, 1200, 1110, 1085, 900, 795; ms *m/z* 492(M$^+$), 446, 421, 407, 380, 295.

2,3,2''-Trifluoro-4-octoxy-4''-pentylterphenyl **(188)**

Quantities: compound **109** (1.40 g, 4.36 mmol), compound **157** (1.50 g, 5.24 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2717 g, 0.235 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.60 g (76%); transitions (°C) K 58.0 S_C 61.5 N 119.5 I;

^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.05(2H, t), 6.82(1H, sext), 7.00(1H, q), 7.04(1H, q), 7.14(1H, sext), 7.38(1H, t), 7.57(2H, q), 7.63(2H, q); ir (KCl) ν_{max} 2960, 2940, 2860, 1635, 1515, 1500, 1470, 1400, 1300, 1195, 1130, 1110, 1090, 900, 805 cm^{-1}; ms *m/z* 482(M$^+$), 425, 370, 313.

4'-Bromo-2,3-difluoro-4-octoxybiphenyl **(189)**

Quantities: compound **184** (3.50 g, 0.012 mol), compound **157** (4.30 g, 0.015 mol), tetrakis(triphenylphosphine)palladium(0) (0.70 g, 0.61 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and was heated under reflux for 2.25 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to yield a colourless solid.

Yield 4.00 g (84%); mp 39-40 °C; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(8H, quint), 1.45(2H, quint), 1.80(2H, quint), 4.05(2H, t), 6.76(1H, sext), 7.02(1H, sext), 7.36(2H, q), 7.53(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1635, 1520, 1495, 1470, 1395, 1315, 1300, 1205, 1075, 1015, 1005, 900, 835, 800 cm^{-1}; ms *m/z* 398(M$^+$), 396(M$^+$).

2,3,2",3"-Tetrafluoro-4-octoxy-4"-pentylterphenyl **(190)**

Quantities: compound **189** (1.70 g, 4.28 mmol), compound **171** (1.35 g, 5.92 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2671 g, 0.23 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethyl acetate to yield colourless crystals.

Yield 1.10 g (51%); transitions (°C) K 111.5 N 120.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.70(2H, t), 4.10(2H, t), 6.84(1H, sext), 7.02(1H, sext), 7.15(2H, 2xsext), 7.60(4H, s); ir (KCl) ν_{max} 2960, 2940, 2860, 1630, 1520, 1470, 1405, 1305, 1200, 1130, 980, 895, 805 $^{-1}$; ms *m/z* 500(M$^+$), 443, 388.

2,3-Difluoro-4-octoxy-4'-pentylbiphenyl **(191)**

Quantities: compound **91** (1.25 g, 5.51 mmol), compound **157** (1.90 g, 6.64 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3424 g, 0.296 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless liquid which was distilled [Kugelrohr, 210 °C (maximum) at 0.1 mmHg] to yield a colourless liquid.

Yield 1.20 g (56%); transitions (°C) K 14.0 (N 13.5) I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.60(2H, t), 4.00(2H, t), 6.76(1H, sext), 7.08(1H, sext), 7.24(2H, d), 7.40(2H, q); ir (film) ν_{max} 2960, 2940, 2860, 1635, 1505, 1470, 1315, 1295, 1200, 1110, 1080, 900, 800 cm^{-1}; ms *m/z* 388(M$^+$), 360, 345, 331, 318, 276.

2,3-Difluoro-4'-heptyl-4-octoxybiphenyl **(192)**

Quantities: compound **92** (1.32 g, 5.18 mmol), compound **157** (1.78 g, 6.22 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3217 g, 0.279 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless liquid which was distilled [Kugelrohr, 230 °C (maximum) at 0.1 mmHg] to yield a colourless liquid.

Yield 1.10 g (51%); transitions (°C) K 24.0 (S$_C$ 6.0 S$_A$ 13.0 N 23.0) I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(16H, m), 1.45(2H, quint), 1.60(2H, quint), 1.80(2H, quint), 2.60(2H, t), 4.05(2H, t), 6.77(1H, sext), 7.07(1H, sext), 7.23(2H, d), 7.41(2H, q); ir (film) ν_{max} 2960, 2940, 2860, 1635, 1505, 1470, 1315, 1295, 1200, 1110, 1080, 900, 800 cm^{-1}; ms *m/z* 416(M$^+$), 398, 381, 364, 354, 346, 331.

2,3-Difluoro-4'-octoxy-4-pentylbiphenyl (**193**)

Quantities: compound **85** (1.58 g, 5.54 mmol), compound **171** (1.55 g, 6.80 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3761 g, 0.326 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless liquid which was distilled [Kugelrohr, 240 °C (maximum) at 0.1 mmHg] to yield a colourless liquid.

Yield 1.69 g (79%); transitions (°C) K 8.0 S_A 12.0 N 18.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.94(1H, sext), 6.97(2H, d), 7.05(1H, sext), 7.46(2H, q); ir (film) ν_{max} 2960, 2940, 2860, 1615, 1525, 1495, 1465, 1415, 1250, 1175, 1115, 895, 840, 815 cm^{-1}; ms *m/z* 388(M$^+$), 366, 358, 331, 309.

2,3-Difluoro-4-heptyl-4'-pentylbiphenyl (**194**)

Quantities: compound **91** (1.35 g, 5.95 mmol), compound **172** (1.85 g, 7.23 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3721 g, 0.322 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to give a colourless liquid which was distilled [Kugelrohr, 210 °C (maximum) at 0.1 mmHg] to yield a colourless liquid.

Yield 1.70 g (80%); transitions (°C) K 0.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.65(4H, m), 2.65(4H, 2xt), 6.96(1H, sext), 7.08(1H, sext), 7.24(2H, d), 7.44(2H, q); ir (film) ν_{max} 2960, 2940, 2860, 1490, 1465, 1410, 1315, 1290, 1220, 1180, 1120, 895 cm^{-1}; ms *m/z* 358(M$^+$), 344, 330, 316, 301.

2,3 Difluoro-4-nonyl-4'-octoxybiphenyl (**195**)

Quantities: compound **85** (1.40 g, 4.91 mmol), compound **173** (1.67 g, 5.88 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2992 g, 0.259 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless liquid which was distilled [Kugelrohr, 230 °C (maximum) at 0.1 mmHg] to yield a colourless liquid.

Yield 0.97 g (37%); transitions (°C) K 25.0 (S_C 11.5) S_A 33.0 N 34.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(20H, m), 1.45(2H, quint), 1.60(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.94(1H, sext), 6.97(2H, d), 7.06(1H, sext), 7.46(2H, q); ir (film) ν_{max} 2960, 2940, 2860, 1610, 1525, 1490, 1465,1250, 1180, 895, 815 cm^{-1}; ms *m/z* 444(M^+), 434, 405, 332, 321, 307.

1-Bromo-4-(*trans*-4-pentylcyclohexylacetyl)benzene (**197**)

Quantities: compound **196** (12.00 g, 0.052 mol), compound **38** (35 ml), aluminium chloride (8.00 g, 0.060 mol).

The experimental procedure was as described for the preparation of compound **88**. The crude product was recrystallised from ethanol to yield an off-white powder.

Yield 10.05 g (55%); mp 73-74 °C; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 0.95(4H, m), 1.15-1.35(9H, 2xm), 1.75(4H, m), 1.90(1H, m), 2.80(2H, d), 7.60(2H, d), 7.80(2H, d); ir (KCl) ν_{max} 2960, 2920, 2850, 1690, 1585, 1450, 1400, 1200, 1075, 1010, 990, 815 cm^{-1}; ms *m/z* 352(M^+), 350(M^+), 326, 306, 294.

1-Bromo-4-(*trans*-4-pentylcyclohexylethyl)benzene (**198**)

Triethylsilane (7.50 g, 0.065 mol) was added slowly dropwise to a stirred, ice-cold solution of compound **197** (9.00 g, 0.026 mol) in trifluoroacetic acid (45.0 g, 0.39 mol). The mixture was stirred at room temperature for 3.25 h (glc analysis revealed a complete reaction) and poured into water. The product was extracted into ether (twice), the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and other volatile fractions were removed by distillation (Kugelrohr) to give a brown liquid which was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a pale yellow liquid.

Yield 5.18 g (60%); ^1H nmr ($CDCl_3$) δ 0.85(7H, m), 1.10-1.30(10H, m), 1.50(2H, m), 1.75(4H, m), 2.55(2H, t), 7.00(2H, d), 7.35(2H, d); ir (film) ν_{max} 2960, 2920, 2850, 1495, 1460, 1075, 1015, 805 cm^{-1}; ms *m/z* 338(M^+), 336(M^+), 319, 292, 282, 280.

2,3-Difluoro-4-octoxy-4'-(*trans*-4-pentylcyclohexylethyl)biphenyl **(199)**

Quantities: compound **198** (1.45 g, 4.30 mmol), compound **157** (1.50 g, 4.30 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2868 g, 0.25 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 6:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.48 g (24%); transitions (°C) K 59.0 S_A 113.5 N 124.0 I; ^1H nmr ($CDCl_3$) δ 0.90(10H, m), 1.30(18H, m), 1.55(4H, m), 1.80(6H, m), 2.70(2H, t), 4.10(2H, t), 6.82(1H, sext), 7.12(1H, sext), 7.28(2H, d), 7.46(2H, q); ir (KCl) ν_{max} 2960, 2940, 2860, 1640, 1510, 1470, 1320, 1305, 1205, 1110, 1080, 900, 800 cm^{-1}; ms *m/z* 498(M^+), 442, 397, 386, 331, 219.

trans-4-Pentylcyclohexylethanal **(201)**

Oxalyl chloride (30.00 g, 0.236 mol) was added dropwise to a stirred, cooled (0 °C) solution of dry DMF (6.15 g, 0.084 mol) in dry dichloromethane (120 ml) under dry nitrogen. The resulting mixture was stirred at 0 °C for 1 h and the solvent was removed *in vacuo* to give a colourless powder. A solution of compound **200** (17.81 g, 0.084 mol) and dry pyridine (6.65 g, 0.084 mol) in dry THF (120 ml) was added dropwise to a stirred, cooled (-30 °C) solution of the colourless powder in dry acetonitrile (120 ml) and dry THF (200 ml) under dry nitrogen. The mixture was stirred at -30 °C for 1 h and then cooled to -78 °C. Copper(I) iodide (1.60 g, 8.40 mmol) was added followed by dropwise addition of a solution of lithium tri-*tert*-butoxyaluminohydride (42.75 g, 0.168 mol) in dry THF (120 ml) at -78 °C. After stirring for 1 h (no further cooling) the reaction mixture was quenched by the dropwise addition of 10% hydrochloric acid at -40 °C and allowed to warm to room temperature. The product was extracted into ether (twice) and the combined ethereal extracts were washed with aqueous sodium hydrogen carbonate, and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was distilled to yield a colourless liquid.

Yield 11.91 g (72%); bp 92-94 °C at 0.5 mmHg; ^1H nmr ($CDCl_3$) δ 0.85(3H, t), 0.95(4H, d), 1.15-1.35(9H, 2xm), 1.77(4H, d), 1.83(1H, m), 2.30(2H, q), 9.75(1H, t); ir (KCl) ν_{max} 2960, 2940, 2860, 1730, 1450, 1380, 900 cm^{-1}; ms *m/z* 152, 123, 109, 96, 81.

1-(2,3-Difluorophenyl)-2-(*trans*-4-pentylcyclohexyl)ethanol (**202**)

Quantities: compound **141** (4.10 g, 0.036 mol), n-butyllithium (3.60 ml, 10.0M in hexane, 0.036 mol), compound **201** (6.80 g, 0.035 mol).

The experimental procedure was as described for the preparation of compound **162**. The crude product was purified by column chromatography (silica gel / dichloromethane) to yield a colourless solid.

Yield 9.20 g (85%); mp 42-43 °C; ^1H nmr ($CDCl_3$) δ 0.85(7H, m), 1.10-1.40(10H, m), 1.55(1H, m), 1.70(4H, m), 1.85(1H, m), 2.05(1H, s), 5.15(1H, q), 7.05(2H, m), 7.20(1H, m); ir (film) ν_{max} 2920, 2860, 1600, 1490, 1280, 1205, 790, 730 cm^{-1}; ms *m/z* 310(M^+), 292, 143.

1,2-Difluoro-3-(*trans*-4-pentylcyclohexylethyl)benzene (**203**)

Quantities: compound **202** (8.95 g, 0.029 mol), triethylsilane (8.42 g, 0.073 mol), trifluoroacetic acid (49.6 g, 0.44 mol).

The experimental procedure was as described for the preparation of compound **126**. Analysis by glc revealed a complete reaction and the presence of a suspected silane byproduct. The crude mixture was distilled [Kugekrohr, 175 °C (maximum) at 0.1 mmHg] in an attempt to isolate the product but the whole mixture distilled over. Analysis by glc of the distillate revealed the presence of starting material in addition to the components present previously. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C)] to yield a colourless oil [the desired product (compound **203**); 2.20 g, 26%] and the eluent was changed to dichloromethane to yield a colourless solid [the starting alcohol (compound **202**); 4.60 g]. Phosphorus(V) oxide (6.75 g, 0.048 mol) was added to a solution of this solid (4.60 g, 0.015 mol) in pentane (80 ml) and this mixture was stirred at room temperature overnight (glc analysis revealed a complete reaction). The mixture was filtered and the filtrate was hydrogenated at room temperature and atmospheric pressure over 5% palladium-on-carbon (0.50 g) for 4 h (glc analysis revealed a complete reaction). The catalyst was removed by filtration and the pentane was removed *in vacuo* to yield a colourless oil (4.25 g, 96%).

Total yield 6.45 g (76%); ^{1}H nmr ($CDCl_3$) δ 0.85-1.00(7H, m), 1.10-1.35(10H, m), 1.50(2H, q), 1.80(4H, m), 2.65(2H, t), 6.90-7.00(3H, m); ir (film) ν_{max} 2980, 2940, 2860, 1630, 1600, 1490, 1285, 1210, 780, 730 cm^{-1}; ms *m/z* 294(M^+), 274, 128.

2,3-Difluoro-4-(*trans*-4-pentylcyclohexylethyl)phenylboronic acid **(204)**

Quantities: compound **203** (5.98 g, 0.020 mol), n-butyllithium (8.10 ml, 2.5M in hexane, 0.020 mol), tri-isopropyl borate (7.60 g, 0.040 mol).

The experimental procedure was as described for the preparation of compound **129**.

Yield 6.80 g (100%); ^{1}H nmr ($CDCl_3$) δ 0.85(7H, m), 1.10-1.35(10H, m), 1.50(2H, quint), 1.80(4H, m), 2.70(2H, t), 7.00(1H, m), 7.45(1H, m), no obvious OH absorption; ir (film) ν_{max} 3600-3100, 2960, 2920, 2860, 1635, 1460, 1420-1300, 1220, 1140, 1060, 1010, 905, 815, 675 cm^{-1}; ms *m/z* 338(M^+), 318, 294, 274, 266, 256.

2,3-Difluoro-4'-octoxy-4-(*trans*-4-pentylcyclohexylethyl)biphenyl (**205**)

Quantities: compound **85** (1.35 g, 4.74 mmol), compound **204** (2.10 g, 6.21 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2161 g, 0.19 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (50:1) to yield colourless crystals.

Yield 1.06 g (45%); transitions (°C) K 32.5 S_C 55.0 S_A 83.0 N 122.0 I; ^{1}H nmr ($CDCl_3$) δ 0.85-0.95(11H, m), 1.10-1.35(16H, m), 1.45(4H, m), 1.65-1.90(7H, m), 2.65(2H, t), 4.00(2H, t), 6.94(1H, sext), 6.96(2H, d), 7.05(1H, sext), 7.46(2H, q); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1520, 1490, 1465, 1250, 1175, 895, 840, 815 cm^{-1}; ms *m/z* 498(M$^+$), 386, 219.

trans-4-Heptylcyclohexylbromomethane (**207**)

Compound **206** (25.00 g, 0.118 mol) was added to a mixture of 48% hydrobromic acid (38 ml) and concentrated sulphuric acid (5 ml); the mixture was heated under strong reflux for 6 h (glc analysis revealed ~80 % conversion). The cooled mixture was poured onto ice and the product was extracted into ether (twice). The combined ethereal extracts were washed with water, aqueous sodium hydrogen carbonate, water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was distilled to yield a colourless oil (80% product, 20% starting material).

Yield 26.91 g (83%); bp 106-108 °C at 0.1 mmHg; no spectroscopic data were obtained.

1-Bromo-4-(*trans*-4-heptylcyclohexylmethoxy)benzene (**208**)

Quantities: compound **207** (10.00 g, 0.036 mol; 80% pure), compound **83** (8.72 g, 0.050 mol), potassium carbonate (15.00 g, 0.109 mol), cyclohexanone (100 ml).

The experimental procedure was as described for the preparation of compound **26**. The solvent and the *trans*-4-heptylcyclohexylmethanol (impurity) were distilled off (0.1

mmHg) and the residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to yield a colourless solid.

Yield 7.75 g (59%); mp 60-61 °C; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.00(4H, q), 1.30(13H, m), 1.80(5H, m), 3.70(2H, d), 6.75(2H, d), 7.35(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1590, 1580, 1490, 1470, 1290, 1245, 1175, 1030, 1005, 825, 805 cm^{-1}; ms *m/z* 368(M$^+$), 366(M$^+$), 194, 174, 172.

2,3-Difluoro-4'-(*trans*-4-heptylcyclohexylmethoxy)-4-pentylbiphenyl **(209)**

Quantities: compound **208** (1.75 g, 4.77 mmol), compound **171** (1.45 g, 6.36 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2761 g, 0.24 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.65 g (29%); transitions (°C) K 54.0 (S$_B$ 42.0) S$_A$ 111.5 N 116.0 I; ^{1}H nmr (CDCl$_3$) δ 0.85(6H, 2xt), 1.00(4H, q), 1.35(17H, m), 1.65(2H, quint), 1.75(5H, m), 2.65(2H, t), 3.85(2H, d), 6.94(1H, sext), 6.79(2H, d), 7.07(1H, sext), 7.45(2H, q); ir (KCl) ν_{max} 2960, 2940, 2860, 1615, 1530, 1500, 1475, 1415, 1320, 1280, 1185, 1120, 1045, 900, 810 cm^{-1}; ms *m/z* 470(M$^+$), 276, 219.

1,2-Difluoro-3-(*trans*-3-heptylcyclohexylmethoxy)benzene **(210)**

Quantities: compound **207** (10.50 g, 0.038 mol; 80% pure), compound **153** (6.00 g, 0.046 mol), potassium carbonate (15.00 g, 0.110 mol), cyclohexanone (100 ml).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 8.00 g (65%); mp 46-47 °C; bp 160-162 °C at 0.1 mmHg; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.00(4H, q), 1.30(13H, m), 1.80(5H, m), 3.80(2H, d), 6.67-6.77(2H, m), 6.89-6.98(1H, m); ir (KCl) ν_{max} 2960, 2940, 2860, 1635, 1620, 1515, 1490, 1470, 1310, 1295, 1260, 1220, 1080, 770, 730, 705 cm^{-1}; ms *m/z* 324 (M$^+$).

Attempted preparation of 2,3-difluoro-4-(*trans*-4-heptylcyclohexylmethoxy)phenylboronic acid (**211**)

Quantities: compound **210** (7.80 g, 0.024 mol), n-butyllithium (2.50 ml, 2.5M in hexane, 0.025 mol), tri-isopropyl borate (10.00 g, 0.053 mol).

The experimental procedure was as described for the preparation of compound **129**.

The product was identified as almost entirely starting material and a small quantity was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to yield a colourless solid.

Yield 2.24 g; mp 46-47 °C; spectroscopic data were identical to those for compound **210**.

1-Bromo-2,3-difluoro-4-(*trans*-4-heptylcyclohexylmethoxy)benzene (**212**)

A solution of bromine (2.00 g, 0.0125 mol) in chloroform (20 ml) was added dropwise to a stirred solution of compound **210** (2.00 g, 6.17 mmol) in chloroform (30 ml) at room temperature. The mixture was heated under reflux for 24 h, cooled and washed with aqueous sodium metabisulphite. The separated aqueous layer was washed with chloroform and the combined organic extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a fawn solid (glc analysis revealed only one product peak).

Yield 2.45 g (100%); mp 62-64 °C; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.05(4H, q), 1.30(13H, m), 1.80(5H, m), 3.80(2H, d), 6.64(1H, sext), 7.18(1H, sext); ir (KCl) ν_{max} 2960, 2920, 2860, 1625, 1510, 1470, 1310, 1220, 1075, 885, 800, 740 cm^{-1}; ms *m/z* 404(M$^+$), 402(M$^+$).

2,3-Difluoro-4-(*trans*-4-heptylcyclohexylmethoxy)-4'-pentylbiphenyl **(213)**

Quantities: compound **212** (2.35 g, 5.83 mmol), compound **94** (1.45 g, 7.55 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3561 g, 0.31 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1 (followed by 20:1)] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals (98.5% pure by hplc).

Yield 1.10 g (40%); transitions (°C) K 51.0 S_A 91.0 N 110.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.05(4H, m), 1.30(17H, m), 1.65(2H, quint), 1.80(5H, m), 2.65(2H, t), 3.90(2H, d), 6.77(1H, sext), 7.08(1H, sext), 7.25(2H, d), 7.42(2H, q); ir (KCl) ν_{max} 2980, 2940, 2860, 1640, 1510, 1470, 1305, 1205, 1110, 1075, 895, 855, 800 cm^{-1}; ms *m/z* 470(M^+), 413, 276.

2,5-Dibromobenzonitrile **(215)**

Bromine (44.0 g, 0.275 mol) was added dropwise to a mixture of compound **214** (10.00 g, 0.097 mol) and aluminium chloride (42.0 g, 0.31 mol) at room temperature. The mixture was heated at 120 °C for 7 h and poured into ice/water. The product was extracted into ether (twice), the combined ethereal extracts were washed with aqueous sodium thiosulphate and dried ($MgSO_4$). The solvent was removed *in vacuo* to give an off-white solid (glc analysis revealed the presence of three components) which was recrystallised from benzene to yield colourless crystals (pure by glc analysis).

Yield 12.15 g (48%); mp 144-145 °C (lit.,[176] 144-145 °C); ^{1}H nmr ($CDCl_3$) δ 7.55(1H, q), 7.60(1H, q), 7.80(1H, q); ir (KCl) ν_{max} 3090, 3060, 2240, 1460, 1380, 1270, 1200, 1090, 1040, 830 cm^{-1}; ms *m/z* 261(M^+), 220, 197, 180, 168, 153.

2'-Cyano-4,4''-dipentylterphenyl **(216)**

Quantities: compound **215** (1.40 g, 5.36 mmol), compound **94** (2.88 g, 0.015 mol), tetrakis(triphenylphosphine)palladium(0) (0.3749 g, 0.325 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 1.13 g (53%); transitions (°C) K 40.0 (S_A 33.5 N 38.0) I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, t), 1.35(8H, m), 1.65(4H, quint), 2.65(4H, t), 7.29(2H, d), 7.31(2H, d), 7.52(4H, d), 7.56(1H, d), 7.83(1H, q), 7.95(1H, d); ir (KCl) ν_{max} 2950, 2920, 2850, 2210, 1600, 1480, 800 cm^{-1}; ms *m/z* 395(M$^+$), 338, 281.

2'-Cyano-4,4"-dihexoxyterphenyl **(217)**

Quantities: compound **215** (1.30 g, 4.98 mmol), compound **86** (3.33 g, 0.015 mol), tetrakis(triphenylphosphine)palladium(0) (0.3554 g, 0.308 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 0.87 g (38%); transitions (°C) K 101.5 (S_C 61.0) S_A 110.0 N 114.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, t), 1.35(8H, m), 1.45(4H, quint), 1.80(4H, quint), 4.00(4H, t), 7.00(2H, d), 7.03(2H, d), 7.52(4H, 2xd), 7.55(1H, d), 7.80(1H, q), 7.90(1H, d); ir (KCl) ν_{max} 2950, 2860, 2220, 1610, 1530, 1490, 1480, 1290, 1250, 1180, 1030, 830 cm^{-1}; ms *m/z* 455(M$^+$), 384, 371, 287.

4-Bromo-2-cyano-4'-pentylbiphenyl **(218)** (method 1)

Quantities: compound **215** (1.80 g, 6.90 mmol), compound **94** (1.20 g, 6.25 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4510 g, 0.390 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and was heated under reflux for 2 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give two fractions:-

(a) two components; compound **216** and compound **218** (product),

(b) two components; compound **215** and 4-bromo-3-cyano-4'-pentylbiphenyl.

The product was purified by distillation (Kugelrohr at 0.1 mmHg) to yield a pale yellow liquid.

Yield 0.42 g (20%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.60(2H, t), 7.30(2H, d), 7.35(1H, d), 7.45(2H, d), 7.70(1H, q), 7.85(1H, d); ir (film) ν_{max} 2980, 2960, 2860, 2250, 1490, 1475, 1390, 1275, 1195, 1100, 1015, 835, 845 cm^{-1}; ms *m/z* 329(M^+), 327(M^+), 272, 270, 190.

See p 184 for method 2.

2'-Cyano-4"-hexoxy-4-pentylterphenyl (**219**)

Quantities: compound **218** (method 1) (0.34 g, 1.0 mmol), compound **86** (0.44 g, 1.98 mmol), tetrakis(triphenylphosphine)palladium(0) (0.1645 g, 0.14 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a colourless solid which was recrystallised from ethanol to give colourless crystals.

Yield 0.26 g (61%); transitions (°C) K 35.5 S_A 97.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.30(2H, d), 7.51(1H, d), 7.53(2H, d), 7.55(2H, d), 7.80(1H, q), 7.90(1H, d); ir (KCl) ν_{max} 2960, 2945, 2860, 2220, 1605, 1485, 1245, 835 cm^{-1}; ms *m/z* 425(M^+), 368, 341, 284.

2-Amino-5-bromobenzonitrile (**221**)

N-Bromosuccinimide (37.7 g, 0.21 mol) was added in small portions over 40 min to a stirred, cooled (-10 to 0 °C) solution of compound **220** (25.00 g, 0.212 mol) in dry dichloromethane (150 ml) under dry nitrogen. The mixture was stirred at 0 °C for 1.25 h (glc analysis revealed a complete reaction) and washed with a large amount of water. The aqueous layer was washed with dichloromethane and the combined organic phases were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a red-purple solid.

Yield 39.0 g (94%); mp 92-94 °C; ^1H nmr ($CDCl_3$) δ 4.50(2H, s), 6.65(1H, d), 7.40(1H, q), 7.50(1H, d); ir (KCl) ν_{max} 3450, 3360, 2220, 1635, 1560, 1490, 1305, 1155 cm^{-1}; ms *m/z* 198(M^+), 196(M^+), 116, 90.

5-Bromo-2-iodobenzonitrile **(222)**

A stirred mixture of compound **221** (25.00 g, 0.127 mol) and 36% hydrochloric acid (110 ml) was warmed gently to obtain a solution, then cooled to -5 °C and a solution of sodium nitrite (10.50 g, 0.152 mol) in water (50 ml) was added dropwise whilst maintaining the temperature at -5 °C. The mixture was stirred at 0 °C for 0.5 h, cyclohexane (100 ml) was added and a solution of potassium iodide (43.5 g, 0.26 mol) in water (100 ml) was added dropwise at between 0 and 5 °C. The mixture was stirred at room temperature for a few hours (overnight for convenience) and the product was extracted into ether (twice). The combined organic extracts were washed with sodium metabisulphite, 10% sodium hydroxide, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give an off-white solid.

Yield 35.0 g (87%); mp 113-114 °C; ^1H nmr ($CDCl_3$) δ 7.40(1H, q), 7.72(1H, d), 7.78(1H, d); ir (KCl) ν_{max} 3090, 3060, 2240, 1450, 1375, 1270, 1195, 1090, 1025, 825 cm^{-1}; ms *m/z* 309(M^+), 307(M^+), 179, 125.

4-Bromo-2-cyano-4'-pentylbiphenyl **(218)** (method 2; for method 1 see p 182)

Quantities: compound **222** (3.50 g, 0.011 mol), compound **94** (2.53 g, 0.013 mol), tetrakis(triphenylphosphine)palladium(0) (0.6421 g, 0.56 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and was heated under reflux for 3 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a pale-yellow liquid.

Yield 2.67 g (74%); spectroscopy details were identical with those for the compound obtained from method 1 (see p 182).

4-Bromo-2-cyano-4'-hexoxybiphenyl **(223)**

Quantities: compound **222** (1.80 g, 5.84 mmol), compound **86** (1.56 g, 7.03 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3572 g, 0.31 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and was heated under reflux for 1.75 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a colourless solid.

Yield 1.72 g (82%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 7.00(2H, d), 7.35(1H, d), 7.45(2H, d). 7.70(1H, q), 7.85(1H, d); ir (KCl) ν_{max} 2955, 2945, 2880, 2240, 1620, 1525, 1480, 1265, 1185 cm^{-1}; ms *m/z* 359(M$^+$), 357(M$^+$), 275, 273, 245, 243.

4-Bromo-2-cyano-4'-octoxybiphenyl **(224)**

Quantities: compound **222** (2.50 g, 8.12 mmol), compound **87** (2.44 g, 9.76 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4927 g, 0.43 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and was heated under reflux for 2 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a colourless solid.

Yield 2.50 g (80%); mp 41-43 °C; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 7.00(2H, d), 7.35(1H, d), 7.45(2H, d), 7.70(1H, q), 7.85(1H, d); ir (KCl) ν_{max} 2960, 2950, 2860, 2240, 1615, 1625, 1475, 1265, 1250, 1185, 1055, 830 cm^{-1}; ms *m/z* 387(M$^+$), 385(M$^+$), 273, 271, 262, 260.

2'-Cyano-4''-octoxy-4-pentylterphenyl (225)

Quantities: compound **218** (1.30 g, 3.96 mmol), compound **87** (1.19 g, 4.76 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2655 g, 0.23 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a off-white solid which was recrystallised from ethanol to yield colourless crystals.

Yield 1.18 g (66%); transitions (°C) K 33.5 S_A 103.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.30(2H, d), 7.51(1H, d), 7.53(2H, d), 7.54(2H, d), 7.75(1H, q), 7.90(1H, d); ir (KCl) ν_{max} 2980, 2960, 2880, 2250, 1620, 1500, 1260, 1200, 835 cm^{-1}; ms *m/z* 453(M$^+$), 396, 341, 283.

2'-Cyano-4-hexoxy-4''-pentylterphenyl (226)

Quantities: compound **223** (1.50 g, 4.19 mmol), compound **94** (1.05 g, 5.47 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3140 g, 0.27 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a pale yellow solid which was recrystallised (charcoal decolourisation) from ethanol to yield colourless crystals.

Yield 0.80 g (44%); transitions (°C) K 48.5 (S_C 29.5) N 77.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.45(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.30(2H, d), 7.51(1H, d), 7.54(4H, d), 7.80(1H, q), 7.95(1H, d); ir (KCl) ν_{max}

2960, 2940, 2860, 2240, 1615, 1490, 1480, 1255, 1190, 830 cm^{-1}; ms *m/z* 425(M$^+$), 341, 284.

2'-Cyano-4-octoxy-4''-pentylterphenyl **(227)**

Quantities: compound **224** (1.48 g, 3.83 mmol), compound **94** (1.01 g, 5.26 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2812 g, 0.34 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a colourless solid which was recrystallised from ethanol to yield colourless crystals.

Yield 1.16 g (67%); transitions (°C) K 35.0 S_C 42.0 N 78.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.50(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 7.00(2H, d), 7.30(2H, d), 7.51(1H, d), 7.54(4H, d), 7.80(1H, q), 7.95(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2230, 1610, 1490, 1475, 1255, 1185, 830 cm^{-1}; ms *m/z* 453(M$^+$), 396, 341, 284.

2-Hexoxybenzonitrile **(229)**

Quantities: compound **228** (8.10 g, 0.068 mol), 1-bromohexane (13.50 g, 0.082 mol), potassium carbonate (18.77 g, 0.136 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 13.11 g (95%); bp 115-118 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(4H, m), 1.45(2H, quint), 1.80(2H, quint), 4.05(2H, t), 6.95(2H, m), 7.50(2H, m); ir (film) ν_{max} 2980, 2960, 2880, 2250, 1610, 1595, 1505, 1465, 1300, 1270, 1175, 1120, 765 cm^{-1}; ms *m/z* 203(M$^+$), 160, 146, 132.

2-Octoxybenzonitrile (**230**)

Quantities: compound **228** (7.50 g, 0.063 mol), 1-bromo-octane (14.00 g, 0.127 mol), potassium carbonate (17.50 g, 0.127 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 13.90 g (96%); bp 130-135 °C at 0.05 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.30(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.05(2H, t), 6.95(2H, m), 7.50(2H, m); ir (film) ν_{max} 2940, 2860, 2240, 1600, 1585, 1495, 1455, 1290, 1265, 1170, 1115, 760 cm^{-1}; ms *m/z* 231(M$^+$), 174, 160, 146, 125, 199.

5-Bromo-2-hexoxybenzonitrile (**231**)

Bromine (19.32 g, 0.121 mol) was added dropwise over 15 min to a stirred solution of compound **229** (12.25 g, 0.060 mol) in chloroform (30 ml) at room temperature. The stirred solution was heated under reflux for 42 h (glc analysis revealed a complete reaction, with only one product peak). The cooled solution was washed with aqueous sodium metabisulphite, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give an off-white solid.

Yield 16.10 g (95%); mp low, around 25 °C; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.45(2H, quint), 1.85(2H, quint), 4.05(2H, t), 6.85(1H, d), 7.58(1H, q), 7.62(1H, d); ir (KCl) ν_{max} 2980, 2940, 2860, 2240, 1600, 1500, 1475, 1400, 1290, 1265, 1140, 1015, 820 cm^{-1}; ms *m/z* 283(M$^+$), 282, 281(M$^+$), 280, 199, 197.

5-Bromo-2-octoxybenzonitrile (**232**)

Quantities: compound **230** (13.50 g, 0.058 mol), bromine (18.70 g, 0.117 mol).

The experimental procedure was as described for the preparation of compound **231**.

Yield 17.50 g (97%); mp 36-37 °C; ^{1}H nmr ($CDCl_3$) δ 0.85(3H, t), 1.25(8H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.85(1H, d), 7.58(1H, q), 7.62(1H, d); ir (KCl) ν_{max} 2980, 2940, 2860, 2250, 1600, 1500, 1480, 1400, 1295, 1265, 1140, 1000, 835 cm^{-1}; ms *m/z* 311(M$^+$), 309(M$^+$), 254, 252, 199, 197.

3-Cyano-4-hexoxy-4''-pentylterphenyl (233)

Quantities: compound **231** (1.55 g, 5.50 mmol), compound **96** (1.91 g, 7.13 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3910 g, 0.34 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 1.10 g (47%); transitions (°C) K 62.0 S_A 163.5 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.10(2H, t), 7.03(1H, d), 7.27(2H, d), 7.54(2H, d), 7.57(2H, d), 7.66(2H, d), 7.76(1H, q), 7.81(1H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 2240, 1610, 1495, 1290, 1125, 815 cm^{-1}; ms *m/z* 425(M$^+$), 368, 341, 284.

3-Cyano-4-octoxy-4''-pentylterphenyl (234)

Quantities: compound **232** (1.55 g, 5.00 mmol), compoumd **96** (1.75 g, 6.53 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3794 g, 0.33 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 1.85 g (82%); transitions (°C) K 62.0 S_A 160.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(6H, 2xt), 1.30(12H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.10(2H, t), 7.03(1H, d), 7.27(2H, d), 7.54(2H, d), 7.57(2H, d), 7.66(2H, d), 7.76(1H, q), 7.81(1H, d), ir (KCl) ν_{max}

2970, 2940, 2860, 2240, 1615, 1500, 1475, 1295, 1270, 1140, 815 cm^{-1}; ms *m/z* 453(M^+), 438, 425, 411, 396, 390, 284.

3"-Cyano-2-fluoro-4"-octoxy-4-pentylterphenyl **(235)**

Quantities: compound **232** (1.30 g, 4.19 mmol), compound **137** (1.56 g, 5.45 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2769 g, 0.24 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol to give colourless crystals.

Yield 1.45 g (73%); transitions (°C) K 48.0 S_A 118.0 I; ^1H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.10(2H, t), 7.00(3H, m), 7.38(1H, t), 7.57(2H, d), 7.63(2H, q), 7.75(1H, q), 7.80(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1625, 1610, 1490, 1290, 1130, 815 cm^{-1}; ms *m/z* 471(M^+), 425, 359, 341, 302.

3-Carboxy-2-fluoro-4-hexoxy-4"-pentylterphenyl **(236)**

n-Butyllithium (1.20 ml, 2.5M in hexane, 3.00 mmol) was added dropwise to a stirred, cooled (-78 °C) solution of compound **107** (1.25 g, 2.99 mmol) in dry THF (80 ml) under dry nitrogen. The mixture was maintained under these conditions for 5 h and poured onto a slurry of dry ice and dry ether. 10% Hydrochloric acid was added, the aqueous layer was washed with ether and the combined ethereal extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a colourless solid.

Yield 1.45 g (tlc analysis revealed the presence of some starting material).

3-Carboxy-2-fluoro-4-octoxy-4"-pentylterphenyl **(237)**

Quantities: compound **108** (1.50 g, 3.36 mmol), n-butyllithium (0.50 ml, 10.0M in hexane, 5.00 mmol).

The experimental procedure was as described for the preparation of compound **236** except that 10.0M butyllithium solution was used and the reaction time was extended to 6 h in order to obtain a greater degree of reaction.

Yield 1.65 g (tlc analysis revealed the presence of some starting material).

3-Cyano-2-fluoro-4-hexoxy-4''-pentylterphenyl **(242)**

A solution of oxalyl chloride (0.80 g, 6.30 mmol) in dry benzene (30 ml) was added dropwise to a stirred solution of compound **236** (1.45 g, 3.14 mmol) in dry benzene (30 ml) and DMF (2 drops) at room temperature. The mixture was stirred at room temperature overnight and the excess of oxalyl chloride and benzene was removed *in vacuo*. The residue was dissolved in diglyme (10 ml) and added dropwise to gently stirred 35% ammonia (25 ml). The resulting precipitate was filtered off and dried ($CaCl_2$) *in vacuo* (0.1 mmHg) to give a colourless solid (1.40 g). A solution of thionyl chloride (3.70 g, 0.03 mol) in dry DMF (30 ml) was added dropwise to a stirred solution of this solid in dry DMF (30 ml). The mixture was stirred at room temperature overnight and poured onto ice/water. The product was extracted into ether (twice), the combined ethereal extracts were washed with water, aqueous sodium hydrogen carbonate, water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 0.20 g (15% based on compound **107**);

transitions (°C) K 100.5 S_A 167.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.10(2H, t), 6.83(1H, q), 7.27(2H, d), 7.54(4H, m), 7.62(1H, t), 7.68(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1625, 1495, 1460, 1400, 1310, 1260, 1100, 1075, 810 cm^{-1}; ms *m/z* 443(M^+), 428, 388, 359, 331, 302.

3-Cyano-2-fluoro-4-octoxy-4''-pentylterphenyl **(243)**

Quantities: compound **237** (1.65 g, 3.37 mmol), oxalyl chloride (1.00 g, 7.87 mmol), 35% ammonia (30 ml), DMF (8 drops), thionyl chloride (4.10 g, 0.034 mol).

The experimental procedure was as described for the preparation of compound **242** except that the product was recrystallised from ethyl acetate.

Yield 0.21 g (13% based on compound **108**);
transitions (°C) K 100.0 S_A 163.5 I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(12H, m), 1.50(2H, quint), 1.65(2H, quint), 1.85(2H, quint), 2.65(2H, t), 4.10(2H, t), 6.83(1H, q), 7.27(2H, d), 7.54(4H, m), 7.62(1H, t), 7.68(2H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 1625, 1490, 1400, 1310, 1075, 810 cm^{-1}; ms *m*/*z* 471(M$^+$), 414, 359, 302.

2-Amino-5-bromobenzotrifluoride **(245)**

Quantities: compound **244** (25.00 g, 0.155 mol), *N*-bromosuccinimide (27.65 g, 0.155 mol).

The experimental procedure was as described for the preparation of compound **221**. The crude product was distilled to yield a colourless liquid.

Yield 35.16 g (95%); bp 100-102 °C at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 4.15(2H, s), 6.60(1H, d), 7.35(1H, q), 7.55(1H, d); ir (KCl) ν_{max} 3530, 3430, 1640, 1615, 1585, 1495, 1430, 1330, 1300, 1265, 1130 cm^{-1}; ms *m*/*z* 241(M$^+$), 239(M$^+$), 221, 219, 194, 192.

5-Bromo-2-Iodobenzotrifluoride **(246)**

Quantities: compound **245** (17.00 g, 0.071 mol), sodium nitrite (5.55 g, 0.080 mol), potassium iodide (23.50 g, 0.142 mol).

The experimental procedure was as described for the preparation of compound **222**.

Yield 24.00 g (98%); mp 63-64 °C; ^{1}H nmr ($CDCl_3$) δ 7.30(1H, q), 7.75(1H, d), 7.85(1H, d); ir (KCl) ν_{max} 1465, 1390, 1305, 1180, 1135, 1010, 890, 825 cm^{-1};

ms *m/z* 352(M^+), 350(M^+), 225, 223.

4-Bromo-2-(trifluoromethyl)-4'-hexoxybiphenyl (**247**)

Quantities: compound **246** (2.80 g, 7.98 mmol), compound **86** (2.20 g, 9.91 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4617 g, 0.40 mmol).

The experimental procedure was as described for the preparation of compound **97** except that the reaction mixture was carefully monitored by glc and tlc analysis and heated under reflux for 1.25 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a pale orange liquid (88% pure by glc, contains 10% starting material).

Yield 3.00 g (94%); ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.45(2H, quint), 1.80(2H, quint), 4.00(2H, t), 6.90(2H, d), 7.15(3H, 2xd), 7.65(1H, q), 7.85(1H, d); ir (KCl) ν_{max} 2980, 2950, 2880, 1620, 1525, 1480, 1310, 1255, 1180, 1140, 1065, 1015, 830 cm^{-1}; ms *m/z* 402(M^+), 400(M^+), 352, 350, 333, 331, 318, 316.

4-Hexoxy-2'-(trifluoromethyl)-4''-pentylterphenyl (**248**)

Quantities: compound **247** (2.75 g, 6.86 mmol, 88% pure), compound **94** (1.80 g, 9.38 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4761 g, 0.41 mmol).

The experimental procedure was as described for the preparation of compound **97**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give an impure orange liquid. Further purification by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) with the gradual introduction of dichloromethane] gave an orange liquid, 37.5% of which was recrystallised from ethanol to yield colourless crystals.

Yield 0.32 g (30% true yield); transitions (°C) K 32.0 (S_C 8.0) I; ^{1}H nmr ($CDCl_3$) δ 0.90(6H, 2xt), 1.35(8H, m), 1.50(2H, quint), 1.65(2H, quint), 1.80(2H, quint), 2.65(2H, t), 4.00(2H, t), 6.92(2H, d), 7.27(2H, d), 7.29(2H, d), 7.38(1H, d), 7.55(2H, d), 7.73(1H, q), 7.93(1H, d); ir (KCl) ν_{max}

2960, 2940, 2860, 1615, 1490, 1330, 1250, 1170, 1130, 1070, 1040, 830 cm^{-1}; ms *m/z* 468(M$^+$), 449, 411, 384, 327.

2-Bromo-6-methoxynaphthalene (**250**)

Dimethylsulphate (33.80 g, 0.268 mol) was added to a stirred solution of compound **249** (50.00 g, 0.224 mol) and potassium hydroxide (15.00 g, 0.268 mol) in water (220 ml) at room temperature. The stirred mixture was heated at 70 °C for 1 h and stirred at room temperature overnight (tlc and glc analysis revealed a complete reaction). The product was filtered off, washed with 10% sodium hydroxide, water and dried well and then extracted into dichloromethane. The organic extract was washed with 10% sodium hydroxide, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to give a colourless solid.

Yield 50.9 g (96%); mp 108-110 °C; ^{1}H nmr ($CDCl_3$) δ 3.90(3H, s), 7.09(1H, d), 7.16(1H, q), 7.49(1H, q), 7.60(1H, d), 7.64(1H, d), 7.91(1H, d); ir (KCl) ν_{max} 1630, 1595, 1500, 1390, 1265, 1215, 1170, 1070, 1035, 905, 855, 820 cm^{-1}; ms *m/z* 238(M$^+$), 236(M$^+$), 223, 221, 208, 206, 195, 193.

2-Bromo-6-butoxynaphthalene (**251**)

Quantities: compound **249** (40.0 g, 0.18 mol), 1-bromobutane (50.0 g, 0.36 mol), potassium carbonate (51.0 g, 0.37 mol).

The experimental procedure was as described for the preparation of compound **26**. The crude product was recrystallised from ethanol to yield an off-white powder.

Yield 32.2 g (64%); mp 52-53 °C; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.55(2H, sext), 2.85(2H, quint), 4.05(2H, t), 7.08(1H, d), 7.15(1H, q), 7.48(1H, q), 7.58(1H, d), 7.63(1H, d), 7.90(1H, q); ir (KCl) ν_{max} 2960, 2950, 2880, 1630, 1590, 1500, 1390, 1260, 1210, 1175, 1070, 920, 890, 850, 830 cm^{-1}; ms *m/z* 280(M$^+$), 278(M$^+$), 224, 222, 195, 193.

6-Butoxynaphth-2-ylboronic acid **(252)**

Quantities: compound **251** (8.60 g, 0.031 mol), n-butyllithium (12.40 ml, 2.5M in hexane, 0.031 mol), tri-isopropyl borate (12.00 g, 0.064 mol).

The experimental procedure was as described for the preparation of compound **129** except that the lithiation was monitored by glc analysis.

Yield 8.50 g (100%) ^{1}H nmr ($CDCl_3$) δ 1.05(3H, t), 1.55(2H, sext), 1.85(2H, quint), 4.10(2H, t), 7.14(1H, d), 7.22(1H, q), 7.82(1H, d), 7.96(1H, d), 8.24(1H, q), 8.72(1H, d) no obvious OH absorption; ir (KCl) ν_{max} 3600-3100, 2960, 2940, 2860, 1630, 1485, 1470, 1385, 1350, 1325, 1205, 805 cm^{-1}; ms *m/z* 590, 579, 565, 552, 536, 522, 509, 496, 480, 465, 255, 200, 144.

2-Butoxy-6-(4-cyanophenyl)naphthalene **(254)**

Quantities: compound **253** (1.25 g, 6.87 mmol), compound **252** (2.01 g, 8.24 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2917 g, 0.25 mmol).

The experimental procedure was as described for the preparation of compound **97** except that glc analysis revealed a complete reaction after 4 h. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (8:1) to yield colourless crystals.

Yield 1.63 g (79%); transitions (°C) K 125.0 N 159.0 I (as lit. values[177]); ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.55(2H, sext), 1.85(2H, quint), 4.00(2H, t), 7.15(1H, d), 7.20(1H, q), 7.65(1H, q), 7.72(2H, d), 7.76(2H, d), 7.78(1H, d), 7.82(1H, d), 7.97(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2230, 1630, 1605, 1500, 1470, 1395, 1255, 1205, 1195, 1135, 1030, 1010, 845, 805 cm^{-1}; ms *m/z* 301(M^+), 273, 245, 227, 216.

2-Iodo-6-methoxynaphthalene **(255)**

A mixture of compound **250** (15.00 g, 0.063 mol), potassium iodide (158.0 g, 0.95 mol) and copper(I) iodide (60.5 g, 0.32 mol) in hexamethylphosphoramide (HMPA)

(180 ml) was stirred at 160 °C under dry nitrogen for 18 h (glc analysis revealed a complete reaction). The cooled mixture was poured into 10% hydrochloric acid (300 ml) and the product was extracted into ether, and left at room temperature overnight. The insoluble copper salts were filtered off and washed well with ether and the separated aqueous layer was washed with ether. The combined ethereal extracts were washed with water, aqueous sodium sulphite, water and dried ($MgSO_4$). The solvent was removed *in vacuo* to yield a pale-yellow solid.

Yield 17.50 g (98%); mp 138-140 °C; ^1H nmr ($CDCl_3$) δ 3.95(3H, s), 7.07(1H, d), 7.13(1H, q), 7.46(1H, d), 7.60(1H, d), 7.65(1H, q), 8.14(1H, d); ir (KCl) ν_{max} 2960, 2940, 2840, 1625, 1580, 1500, 1390, 1265, 1215, 1035, 900, 855, 820 cm^{-1}; ms *m/z* 284(M^+), 269, 241.

2-Butoxy-6-iodonaphthalene **(256)**

Quantities: compound **251** (20.00 g, 0.072 mol), potassium iodide (180.0 g, 1.08 mol), copper(I) iodide (68.6 g, 0.36 mol), HMPA (220 ml).

The experimental procedure was as described for the preparation of compound **255**.

Yield 22.75 g (97%); mp 66-67 °C; ^1H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.05(2H, t), 7.05(1H, d), 7.13(1H, q), 7.45(1H, d), 7.60(1H, d), 7.64(1H, q), 8.12(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1625, 1585, 1500, 1460, 1390, 1260, 1215, 1170, 915, 890, 855, 825 cm^{-1}; ms *m/z* 326(M^+), 270, 200, 143.

6-Methoxynaphth-2-ylethyne **(257)**

A solution of zinc chloride (13.35 g, 0.098 mol) in dry THF (100 ml) was added dropwise to a stirred, cooled (-5 to 0 °C) solution of lithium acetylide ethylenediamine complex (9.00 g, 0.098 mol) in dry THF (100 ml) under dry nitrogen. The mixture was stirred at 10 °C for 30 min and a solution of compound **255** (10.00 g, 0.035 mol) in dry THF (50 ml) was added dropwise at -5 to 0 °C followed by the addition of tetrakis(triphenylphosphine)palladium(0) (1.62 g, 1.40 mmol). The mixture was stirred at room temperature overnight (glc analysis revealed a complete reaction). The mixture was poured into 10% hydrochloric acid and the product was extracted into ether (twice) and the combined ethereal extracts were washed with aqueous sodium hydrogen carbonate and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to give a colourless solid.

Yield 4.18 g (66%); mp 97-98 °C; ^{1}H nmr ($CDCl_3$) δ 3.10(1H, s), 3.90(3H, s), 7.09(1H, d), 7.15(1H, q), 7.48(1H, q), 7.67(1H, d), 7.69(1H, d), 7.95(1H, d); ir (KCl) ν_{max} 3280, 2110, 1630, 1605, 1505, 1485, 1390, 1260, 1230, 1170, 1035, 905, 860, 820 cm^{-1}; ms *m/z* 182(M^+), 167, 139.

6-Butoxynaphth-2-ylethyne (**258**)

Quantities: lithium acetylide ethylenediamine complex (8.50 g, 0.092 mol), zinc chloride (12.60 g, 0.093 mol), compound **256** (12.00 g, 0.037 mol), tetrakis(triphenylphosphine)palladium(0) (2.15 g, 1.86 mmol).

The experimental procedure was as described for the preparation of compound **257**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to yield a colourless solid.

Yield 6.76 g (82%); mp 35-36 °C; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 3.10(1H, s), 4.05(2H, t), 7.08(1H, d), 7.15(1H, q), 7.47(1H, q), 7.64(1H, d), 7.68(1H, d), 7.93(1H, d); ir (KCl) ν_{max} 3320, 2960, 2940, 2880, 2120, 1635, 1605, 1505, 1470, 1395, 1270, 1230, 1175, 1125, 895, 855, 815 cm^{-1}; ms *m/z* 224(M^+), 168, 150, 139.

1-(6-Methoxynaphth-2-yl)-2-(4-cyanophenyl)ethyne (**259**)

Quantities: compound **257** (3.86 g, 0.021 mol), n-butyllithium (8.50 ml, 2.5M in hexane, 0.021 mol), zinc chloride (2.86 g, 0.021 mol), compound **253** (3.86 g, 0.021 mmol), tetrakis(triphenylphosphine)palladium(0) (0.97 g, 0.84 mmol).

The experimental procedure was similar to that described for the preparation of compound **21** except that the reaction mixture was heated at 50 °C for 18 h (glc and tlc analysis revealed a complete reaction). The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a pale yellow solid (4.68 g, 79%). A small quantity (0.50 g) was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless fluorescent crystals (0.30 g).

Yield 4.68 g (79%); transitions (°C) K 144.0 N 210.0 I; ^{1}H nmr ($CDCl_3$) δ 3.95(3H, s), 7.13(1H, d), 7.18(1H, q), 7.53(1H, q), 7.61(2H, d), 7.66(2H, d), 7.71(1H, d), 7.73(1H, d), 8.00(1H, d); ir (KCl) ν_{max} 2240, 1610, 1480, 1390, 1260, 1215, 1170, 1140, 1025, 860, 835 cm^{-1}; ms *m/z* 283(M$^+$), 268.

1-(6-Butoxynaphth-2-yl)-2-(4-cyanophenyl)ethyne **(260)**

Quantities: compound **258** (1.80 g, 8.04 mmol), n-butyllithium (3.30 ml, 2.5M in hexane, 8.25 mmol), zinc chloride (1.15 g, 8.46 mmol), compound **253** (1.42 g, 7.80 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4691 g, 0.41 mmol).

The experimental procedure was as described for the preparation of compound **21**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (20:1) to yield colourless (fluorescent) crystals.

Yield 1.45 g (57%); transitions (°C) K 106.5 / 111.5 N 186.0 I; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.55(2H, sext), 1.85(2H, quint), 4.10(2H, t), 7.12(1H, d), 7.18(1H, q), 7.52(1H, q), 7.61(2H, d), 7.66(2H, d), 7.70(1H, d), 7.73(1H, d), 7.99(1H, d); ir (KCl) ν_{max} 2980, 2880, 2220, 1610, 1475, 1395, 1260, 1215, 1175, 1140, 1040, 1010, 840, 835 cm^{-1}; ms *m/z* 325(M$^+$), 269, 240.

1-Butoxy-4-iodobenzene **(262)**

Quantities: compound **261** (44.0 g, 0.20 mol), 1-bromobutane (45.0 g, 0.33 mol), potassium carbonate (56.0 g, 0.41 mol).

The experimental procedure was as described for the preparation of compound **26** and the crude product was distilled.

Yield 51.81 g (94%); bp 108-110 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.95(3H, t), 1.45(2H, sext), 1.75(2H, quint), 3.90(2H, t), 6.65(2H, d), 7.60(2H, d); ir (film) ν_{max} 2960, 2940, 2860, 1590, 1575, 1485, 1475, 1285, 1245, 1175, 1000, 820 cm^{-1}; ms *m/z* 276(M$^+$), 220, 143.

4-Butoxyphenylethyne (**263**)

Quantities: lithium acetylide ethylenediamine complex (21.00 g, 0.228 mol), zinc chloride (31.1 g, 0.23 mol), compound **262** (24.00 g, 0.087 mol), tetrakis(triphenylphosphine)palladium(0) (3.17 g, 0.27 mol).

The experimental procedure was similar to that described for the preparation of compound **257** except that the crude product was filtered through a short alumina column to remove some of the catalyst and then distilled.

Yield 7.60 g (50%); bp 80-82 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.95(3H, t), 1.45(2H, sext), 1.75(2H, quint), 3.00(1H, s), 3.95(2H, t), 6.80(2H, d), 7.40(2H, d); ir (film) ν_{max} 3300, 2960, 2940, 2880, 2120, 1610, 1510, 1475, 1295, 1250, 1175, 835 cm^{-1}; ms *m/z* 174(M$^+$), 118, 89.

1-Iodo-4-pentylbenzene (**265**)

Quantities: compound **264** (20.00 g, 0.12 mol), 36% hydrochloric acid (110 ml), sodium nitrite (10.50 g, 0.15 mol), potassium iodide (43.5 g, 0.26 mol).

The experimental procedure was as described for the preparation of compound **222** and the crude product was distilled.

Yield 29.00 g (88%); bp 90-95 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.25(4H, m), 1.55(2H, quint), 2.50(2H, t), 6.90(2H, d), 7.55(2H, d); ir (film) ν_{max} 2960, 2940, 2860, 1490, 1405, 1065, 1010, 795 cm^{-1}; ms *m/z* 274(M$^+$), 217.

4-Pentylphenylethyne **(266)**

Quantities: lithium acetylide ethylenediamine complex (20.25 g, 0.22 mol), zinc chloride (30.0 g, 0.22 mol), compound **265** (24.00 g, 0.088 mol), tetrakis(triphenylphosphine)palladium(0) (3.12 g, 2.70 mmol).

The experimental procedure was as described for the preparation of compound **263**.

Yield 7.80 g (52%); bp 122-123 °C at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.55(2H, quint), 2.55(2H, t), 3.00(1H, s), 7.10(2H, d), 7.40(2H, d); ir (film) ν_{max} 3320, 2960, 2880, 2130, 1620, 1520, 1480, 1125, 1030, 850, 830, 660, 655, 620, 565 cm^{-1}; ms *m/z* 172(M^+), 115.

1-(6-Butoxynaphth-2-yl)-2-(4-butoxyphenyl)ethyne **(267)**

Quantities: compound **263** (1.10 g, 6.32 mmol), n-butyllithium (2.60 ml, 2.5M in hexane, 6.50 mmol), zinc chloride (0.90 g, 6.62 mmol), compound **256** (2.00 g, 6.13 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3721 g, 0.32 mmol).

The experimental procedure was as described for the preparation of compound **21**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (20:1) to yield colourless crystals. Note: glc analysis revealed the presence of some starting material (compound **256**) which was isolated during purification as a colourless solid (0.33 g).

Yield 0.22 g (22%); transitions (°C) K 149.0 N 178.5 I; ^{1}H nmr ($CDCl_3$) δ 1.00(6H, 2xt), 1.55(4H, m), 1.80(4H, m), 3.95(2H, t), 4.05(2H, t), 6.87(2H, d), 7.10(1H, d), 7.14(1H, q), 7.47(2H, d), 7.53(1H, q), 7.66(1H, d), 7.70(1H, d), 7.94(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1620, 1600, 1515, 1470, 1395, 1390, 1250, 1210, 1175, 900, 865, 835 cm^{-1}; ms *m/z* 372(M^+), 316, 260.

1-(6-Butoxynaphth-2-yl)-2-(4-pentylphenyl)ethyne **(268)**

Quantities: compound **266** (1.35 g, 7.85 mmol), n-butyllithium (3.20 ml, 2.5M in hexane, 8.00 mmol), zinc chloride (1.15 g, 8.45 mmol), compound **256** (2.35 g, 8.45 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3101 g, 0.27 mmol).

The experimental procedure was as described for the preparation of compound **21**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 12:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (20:1) to yield colourless crystals.

Yield 1.70 g (64%); transitions (°C) K 82.0 N 143.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.05(3H, t), 1.35(4H, m), 1.65(4H, m), 1.85(2H, quint), 2.65(2H, t), 4.10(2H, t), 7.10(1H, d), 7.14(1H, q), 7.18(2H, d), 7.47(2H, d), 7.54(1H, q), 7.67(1H, d), 7.71(1H, d), 7.96(1H, d); ir (KCl) ν_{max} 2980, 2940, 2860, 1630, 1605, 1470, 1390, 1260, 1210, 1175, 1140, 1070, 1025, 980, 965, 865, 850, 820 cm^{-1}; ms *m/z* 370(M^+), 355, 314, 257.

1-(6-Methoxynaphth-2-yl)-2-(4-butoxyphenyl)ethyne (**269**)

Quantities: compound **263** (2.50 g, 0.014 mol), n-butyllithium (5.75 ml, 2.5M in hexane, 0.014 mol), zinc chloride (2.00 g, 0.015 mol), compound **250** (2.80 g, 0.012 mol), tetrakis(triphenylphosphine)palladium(0) (0.6939 g, 0.60 mmol).

The experimental procedure was similar to that described for the preparation of compound **21** except that the mixture was heated under reflux (oil bath at 100 °C) for 22 h (overnight for convenience; glc and tlc analysis revealed a complete reaction). The crude mixture was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (1:1) to yield colourless crystals.

Yield 2.55 g (64%); transitions (°C) K 131.0 N 185.0 I; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 3.90(3H, s), 4.00(2H, t), 6.88(2H, d), 7.10(1H, d), 7.15(1H, q), 7.48(2H, d), 7.53(1H, q), 7.68(1H, d), 7.70(1H, d), 7.95(1H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 1600, 1515, 1485, 1390, 1260, 1250, 1215, 1170, 1035, 900, 860, 825 cm^{-1}; ms *m/z* 330(M^+), 315, 274, 259.

1-Bromo-4-pent-1-ynylbenzene **(270)**

Quantities: pent-1-yne (5.28 g, 0.078 mol), n-butyllithium (7.80 ml, 10.0M in hexane, 0.078 mol), zinc chloride (10.80 g, 0.079 mol), compound **184** (5.28 g, 0.078 mol), tetrakis(triphenylphosphine)palladium(0) (2.80 g, 2.40 mmol).

The experimental procedure was as described for the preparation of compound **21**.

Yield 14.20 g (82%); bp 130-134 °C at 15 mmHg; ^{1}H nmr ($CDCl_3$) δ 1.05(3H, t), 1.60(2H, sext), 2.35(2H, t), 7.20(2H, d), 7.40(2H, d); ir (film) ν_{max} 2960, 2940, 2860, 1485, 1395, 1340, 1070, 1010, 1000, 820 cm^{-1}; ms *m/z* 224(M$^+$), 223, 222(M$^+$), 221, 209, 207, 202, 200, 185, 183.

1-(6-Butoxynaphth-2-yl)-2-(4-pent-1-ynylphenyl)ethyne **(271)**

Quantities: compound **258** (1.60 g, 7.14 mmol), n-butyllithium (2.90 ml, 2.5M in hexane, 7.25 mmol), zinc chloride (1.00 g, 7.35 mmol), compound **270** (1.57 g, 7.04 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4129 g, 0.36 mmol).

The experimental procedure was as described for the preparation of compound **269**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to yield a colourless solid which was recrystallised from ethanol-ethyl acetate (1:1) to yield colourless crystals.

Yield 1.77 g (77%); transitions (°C) K 126.5 N 171.0 I; ^{1}H nmr ($CDCl_3$) δ 0.95(3H, t), 1.05(3H, t), 1.50(2H, sext), 1.65(2H, sext), 1.85(2H, quint), 2.40(2H, t), 4.10(2H, t), 7.10(1H, d), 7.17(1H, q), 7.37(2H, d), 7.47(2H, d), 7.52(1H, q), 7.67(1H, d), 7.71(1H, d), 7.96(1H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 1625, 1600, 1470, 1390, 1260, 1215, 1175, 860, 840, 820 cm^{-1}; ms *m/z* 366(M$^+$), 337, 323, 310, 281.

1-(6-Butoxynaphth-2-yl)-2-(3-fluoro-4-pent-1-ynylphenyl)ethyne **(272)**

Quantities: compound **258** (1.30 g, 5.80 mmol), n-butyllithium (3.65 ml, 1.6M in hexane, 5.84 mmol), zinc chloride (0.80 g, 5.88 mmol), compound **114** (1.47 g, 6.10 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2394 g, 0.21 mmol).

The experimental procedure was as described for the preparation of compound **269**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 1.31 g (59%); transitions (°C) K 102.5 S_A 108.5 N 144.0 I; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.05(3H, t), 1.55(2H, sext), 1.65(2H, sext), 1.85(2H, quint), 2.45(2H, t), 4.10(2H, t), 7.10(1H, d), 7.16(1H, q), 7.23(1H, q), 7.25(1H, q), 7.37(1H, t), 7.51(1H, q), 7.67(1H, d), 7.71(1H, d), 7.97(1H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 2210, 1615, 1475, 1395, 1260, 1220, 1195, 1040, 1010, 890, 865, 825 cm^{-1}; ms *m/z* 384(M^+), 328, 299.

1-Bromo-3-fluoro-4-butoxybenzene **(273)**

Quantities: compound **99** (11.60 g, 0.061 mol), 1-bromobutane (10.00 g, 0.073 mol), potassium carbonate (25.0 g, 0.18 mol), butanone (130 ml).

The experimental procedure was as described for the preparation of compound **26**. Yield 9.50 g (63%); bp 80-82 °C at 0.1 mmHg; ^{1}H nmr ($CDCl_3$) δ 0.95(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.80(1H, t), 7.14(1H, oct), 7.20(1H, q); ir (KCl) ν_{max} 2980, 2960, 2880, 1585, 1505, 1475, 1410, 1310, 1270, 1210, 1135, 1075, 1030, 1010, 880, 860, 805, 640, 580 cm^{-1}; ms *m/z* 248(M^+), 246(M^+), 192, 190.

1-(6-Butoxynaphth-2-yl)-2-(3-fluoro-4-butoxyphenyl)ethyne **(274)**

Quantities: compound **258** (1.44 g, 6.43 mmol), n-butyllithium (2.60 ml, 2.5M in hexane, 6.50 mmol), zinc chloride (0.90 g, 6.62 mmol), compound **273** (1.65 g, 6.68 mmol), tetrakis(triphenylphosphine)palladium(0) (0.3127 g, 0.27 mmol).

The experimental procedure was as described for the preparation of compound **269**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 3:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.22 g (49%); transitions (°C) K 132.0 N 153.0 I; ^{1}H nmr ($CDCl_3$) δ 1.00(6H, 2xt), 1.50(4H, sext), 1.80(4H, quint), 4.05(4H, 2xt), 6.91(1H, t), 7.09(1H, d), 7.15(1H, q), 7.27(2H, 2xq), 7.50(1H, q), 7.66(1H, d), 7.70(1H, d), 7.94(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1515, 1270, 1240, 1050, 1020, 830, 770 cm^{-1}; ms *m*/*z* 390(M^+), 347, 334, 278.

The attempted preparation of 4-pent-1-ynylphenylethyne (**275**)

Quantities: lithium acetylide ethylenediamine complex (6.20 g, 0.067 mol), zinc chloride (9.20 g, 0.068 mol), compound **270** (5.00 g, 0.022 mol), tetrakis(triphenylphosphine)palladium(0) (1.50 g, 1.30 mmol).

The experimental procedure was similar to that described for the preparation of compound **257** except that the reaction mixture was heated under reflux for 4 h (*i.e.*, until glc analysis revealed a complete reaction). The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1 with the gradual addition of further dichloromethane] to give a yellow solid which was recrystallised from hexane to yield colourless crystals [1,2-di(4-pent-1-ynylphenyl)ethyne].

Yield 1.90 g (56%); transitions (°C) K 121.0 I; ^{1}H nmr ($CDCl_3$) δ 1.05(6H, t), 1.60(4H, sext), 2.40(4H, t), 7.35(4H, d), 7.45(4H, d); ir (KCl) ν_{max} 2960, 2940, 2890, 2860, 2840, 1520, 1460, 1410, 1285, 1115, 845, 550 cm^{-1}; ms *m*/*z* 310(M^+), 295, 281.

2-Cyano-6-methoxynaphthalene (**276**)

A mixture of compound **250** (12.00 g, 0.051 mol) and copper(I) cyanide (5.26 g, 0.059 mol) in dry DMF (75 ml) was heated at 185 °C for 5 h (glc analysis revealed a complete reaction). The cooled mixture was poured into 10% hydrochloric acid and the product was extracted into ether. The insoluble salts were filtered off and the separated aqueous layer was washed with ether. The combined ethereal extracts were washed with brine and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) -

dichloromethane, 1:2] to give a pale yellow solid.

Yield 7.60 g (81%); mp 103-104 °C; ^{1}H nmr ($CDCl_3$) δ 3.95(3H, s), 7.15(1H, d), 7.24(1H, q), 7.58(1H, q), 7.80(2H, d), 8.15(1H, d); ir (KCl) ν_{max} 3080, 3010, 2940, 2850 (all weak), 2220, 1625, 1605, 1480, 1390, 1270, 1230, 1175, 1030, 895, 875, 815, 665, 550, 475 cm^{-1}; ms *m/z* 183(M^+), 168, 153, 140.

6-Cyanonaphth-2-ol **(277)**

Quantities: compound **276** (6.90 g, 0.0377 mol), boron tribromide (24.00 g, 10.0 ml, 0.0956 mol).

The experimental procedure was as described for the preparation of compound **11**. Yield 6.40 g (100%), mp 156-157 °C; ^{1}H nmr ($CDCl_3$) δ 7.19(1H, d), 7.24(1H, q), 7.50(1H, q), 7.70(1H, d), 7.76(1H, d), 8.11(1H, d), 9.65(1H, s); ir (KCl) ν_{max} 3400-3100, 2240, 1625, 1485, 1395, 910, 870 cm^{-1}; ms *m/z* 169(M^+).

6-Cyanonaphth-2-yl triflate **(278)**

A solution of *N*-phenyltriflamide (9.00 g, 0.025 mol) in dry dichloromethane (50 ml) was added dropwise to a stirred, cooled (-78 °C) solution of compound **277** (4.00 g, 0.024 mol) in dry dichloromethane (80 ml) and dry triethylamine (4.90 g, 0.049 mol) under dry nitrogen. The stirred mixture was allowed to warm to room temperature overnight (glc and tlc analysis revealed a complete reaction). The mixture was washed with aqueous sodium carbonate and the separated aqueous layer was washed with dichloromethane. The combined organic extracts were washed with water and dried ($MgSO_4$). The solvent was removed *in vacuo* and the residue was purified by column chromatography (silica gel / dichloromethane) to give a colourless solid.

Yield 7.20 g (99%); mp 93-94 °C; ^{1}H nmr ($CDCl_3$) δ 7.52(1H, q), 7.73(1H, q), 7.83(1H, d), 7.99(1H, d), 8.03(1H, d), 8.30(1H, d); ir (KCl) ν_{max} 3080, 2240, 1425, 1250, 1235, 1210, 1140, 1120, 940, 880, 825, 665, 625, 610 cm^{-1}; ms *m/z* 301(M^+), 276, 237, 168, 140.

1-(6-Cyanonaphth-2-yl)-2-(4-butoxyphenyl)ethyne (**279**)

Quantities: compound **263** (1.28, 7.36 mmol), n-butyllithium (2.95 ml, 2.5M in hexane, 7.38 mmol), zinc chloride (1.05 g, 7.72 mmol), compound **278** (2.10 g, 6.98 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4267 g, 0.37 mmol), lithium chloride (0.6171 g, 0.015 mol).

The experimental procedure was similar to that described for the preparation of compound **269** except that lithium chloride was added with the tetrakis(triphenylphosphine)palladium(0). The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a pale-yellow solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless (fluorescent) crystals.

Yield 1.64 g (72%); transitions (°C) K 110.5 / 120.5 N 195.5 I; ^{1}H nmr ($CDCl_3$) δ 1.00(3H, t), 1.50(2H, sext), 1.80(2H, quint), 4.00(2H, t), 6.90(2H, d), 7.50(2H, d), 7.61(1H, q), 7.67(1H, q), 7.84(1H, d), 7.87(1H, d), 8.03(1H, d), 8.19(1H, d); ir (KCl) ν_{max} 2960, 2950, 2880, 2240, 2210, 1610, 1600, 1520, 1475, 1290, 1260, 900, 850, 830 cm^{-1}; ms *m/z* 325(M$^+$), 269, 240.

1-(6-Cyanonaphth-2-yl)-2-(4-pentylphenyl)ethyne (**280**)

Quantities: compound **266** (1.29 g, 7.50 mmol), n-butyllithium (3.00 ml, 2.5M in hexane, 7.50 mmol), zinc chloride (1.05 g, 7.72 mmol), compound **278** (2.12 g, 7.04 mmol), tetrakis(triphenylphosphine)palladium(0) (0.4361 g, 0.38 mmol), lithium chloride (0.6269 g, 0.015 mmol).

The experimental procedure was as described for the preparation of compound **279**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 2:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (10:1) to yield colourless crystals.

Yield 1.42 g (62%); transitions (°C) K 79.5 N 164.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.30(4H, m), 1.60(2H, quint), 2.60(2H, t), 7.20(2H, d), 7.49(2H, d), 7.62(1H, q), 7.68(1H, q), 7.86(1H, d), 7.89(1H, d), 8.06(1H, d), 8.20(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 2210, 1625, 1510, 900, 890, 840, 815 cm^{-1}; ms *m/z* 323(M$^+$), 266.

1-(6-Butoxynaphth-2-yl)-2-(6-cyanonaphth-2-yl)ethyne (**281**)

Quantities: compound **258** (1.60 g, 7.14 mmol), n-butyllithium (2.90 ml, 2.5M in hexane, 7.25 mmol), zinc chloride (1.00 g, 7.35 mmol), compound **278** (2.00 g, 6.64 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2621 g, 0.23 mmol), lithium chloride (0.5812 g, 0.014 mol).

The experimental procedure was as described for the preparation of compound **279**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 1:1] to give a yellow solid which was recrystallised from ethyl acetate to yield pale-yellow crystals.

Yield 1.42 g (57%); transitions (°C) K 185.0 N 270.5 I; ^{1}H nmr (CDCl$_3$) δ 1.00(3H, t), 1.55(2H, sext), 1.85(2H, quint), 4.10(2H, t), 7.12(1H, d), 7.18(1H, q), 7.56(1H, q), 7.62(1H, q), 7.70(1H, d), 7.71(1H, q), 7.73(1H, d), 7.87(1H, d), 7.90(1H, d), 8.02(1H, d), 8.10(1H, d), 8.21(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 2240, 2210, 1620, 1600, 1500, 1470, 1275, 1215, 1160, 910, 900, 880, 820, 660 cm^{-1}; ms *m/z* 375(M$^+$), 319, 290.

6-Bromonaphth-2-yl triflate (**282**)

Quantities: compound **249** (2.80 g, 0.0126 mol), *N*-phenyltriflamide (4.93 g, 0.0138 mol), triethylamine (2.55 g, 0.025 mol).

The experimental procedure was as described for the preparation of compound **278**. The crude product was purified by column chromatography (silica gel / dichloromethane) to give an off-white solid.

Yield 4.40 g (98%); mp 52-53 °C; ^{1}H nmr (CDCl$_3$) δ 7.37(1H, q), 7.61(1H, q), 7.69(1H, d), 7.71(1H, d), 7.79(1H, d), 8.01(1H, d); ir (KCl) ν_{max} 1595, 1505, 1420, 1250, 1210, 1200, 1145, 1110, 920, 890, 880, 805, 720, 660, 610 cm^{-1}; ms *m/z* 355(M$^+$), 353(M$^+$), 223, 221, 195, 193.

1-(6-Bromonaphth-2-yl)-2-(4-pentylphenyl)ethyne (**283**)

Quantities: compound **266** (2.30 g, 0.013 mol), n-butyllithium (5.20 ml, 2.5M in hexane, 0.013 mol), zinc chloride (1.80 g, 0.013 mol), compound **282** (3.90 g, 0.011 mol), tetrakis(triphenylphosphine)palladium(0) (0.6357 g, 0.55 mol), lithium chloride (0.95 g, 0.022 mol).

The experimental procedure was as described for the preparation of compound **279**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 10:1] to give a yellow solid which was recrystallised from ethanol-ethyl acetate (3:1) to give colourless crystals.

Yield 1.91 g (46 %); transitions (°C) K 106.5 N 145.0 I; ^{1}H nmr ($CDCl_3$) δ 0.90(3H, t), 1.35(4H, m), 1.65(2H, quint), 2.65(2H, t), 7.18(2H, d), 7.48(2H, d), 7.55(1H, q), 7.59(1H, q), 7.67(1H, d), 7.71(1H, d), 7.97(1H, d), 7.99(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1590, 1515, 1470, 1270, 1170, 1145, 1070, 905, 895, 830, 655 cm^{-1}; ms *m*/*z* 378(M^+), 376, 321, 319.

6-Iodonaphth-2-ol (**284**)

Quantities: compound **255** (10.00 g, 0.035 mol), boron tribromide (10.0 ml, 22.00 g, 0.088 mol).

The experimental procedure was as described for the preparation of compound **11**. Yield 9.45 g (100%); mp 129-131 °C; ^{1}H nmr ($CDCl_3$) δ 5.15(1H, s), 7.07(1H, d), 7.09(1H, q), 7.40(1H, d), 7.61(1H, d), 7.63(1H, q), 8.13(1H, d); ir (KCl) ν_{max} 3500-3000, 1630, 1585, 1505, 1395, 1350, 1260, 1210, 905, 860, 815 cm^{-1}; ms *m*/*z* 270(M^+), 182, 143.

6-Iodonaphth-2-yl triflate (**285**)

Quantities: compound **284** (6.00 g, 0.022 mol), *N*-phenyltriflamide (8.35 g, 0.023 mol), triethylamine (4.50 g, 0.045 mol).

The experimental procedure was as described for the preparation of compound **278**. The crude product was purified by column chromatography (silica gel /

dichloromethane) to give a fawn solid.

Yield 8.80 g (100%); mp 65-66 °C; ^1H nmr ($CDCl_3$) δ 7.38(1H, q), 7.60(1H, d), 7.71(1H, d), 7.80(1H, d), 7.82(1H, q), 8.30(1H, d); ir (KCl) ν_{max} 1500, 1420, 1210, 1200, 1145, 1110, 960, 915, 880, 805, 720, 650, 605 cm^{-1}; ms *m/z* 402(M^+), 269, 241.

6-Pent-1-ynylnaphth-2-yl triflate **(286)**

Quantities: pent-1-yne (1.60 g, 0.0235 mol), n-butyllithium (2.35 ml, 10.0M in hexane, 0.0235 mol), zinc chloride (3.20 g, 0.0235 mol), compound **285** (8.20 g, 0.020 mol), tetrakis(triphenylphosphine)palladium(0) (1.20 g, 1.0 mmol).

The experimental procedure was as described for the preparation of compound **21**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a pale yellow oil.

Yield 6.33 g (92%); ^1H nmr ($CDCl_3$) δ 1.10(3H, t), 1.70(2H, sext), 2.45(2H, t), 7.34(1H, q), 7.53(1H, q), 7.68(1H, d), 7.75(1H, d), 7.81(1H, d), 7.92(1H, d); ir (film) ν_{max} 2980, 2950, 2880, 2240, 1605, 1505, 1430, 1250, 1220, 1145, 1110, 960, 920, 890, 860, 810 cm^{-1}; ms *m/z* 342(M^+), 313, 209.

1-(6-Pent-1-ynylnaphth-2-yl)-2-(4-butoxyphenyl)ethyne **(287)**

Quantities: compound **263** (1.10 g, 6.32 mmol), n-butyllithium (3.95 ml, 1.6M in hexane, 6.33 mmol), zinc chloride (0.90 g, 6.61 mmol), compound **286** (2.05 g, 6.00 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2414 g, 0.21 mmol), lithium chloride (0.5810 g, 0.014 mol).

The experimental procedure was as described for the preparation of compound **279**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 4:1] to give a colourless solid which was recrystallised from ethanol-ethyl acetate (1:1) to yield colourless crystals.

Yield 1.41 g (64%); transitions (°C) K 124.0 N 172.0 I; ^1H nmr ($CDCl_3$) δ 0.95(3H, t), 1.10(3H, t), 1.50(2H, sext), 1.65(2H, sext), 1.80(2H, quint), 2.45(2H, t), 4.00(2H, t), 6.88(2H, d), 7.45(1H, q), 7.48(2H, d), 7.54(1H, q), 7.71(2H, 2xd), 7.86(1H, d), 7.96(1H, d); ir (KCl) ν_{max} 2960, 2940, 2860, 1610, 1600, 1520, 1475, 1290, 1250, 1180, 1110, 905, 840, 830 cm^{-1}; ms *m/z* 366(M$^+$), 281.

1-(6-Pent-1-ynylnaphth-2-yl)-2-(4-pentylphenyl)ethyne (**288**)

Quantities: compound **266** (1.08 g, 6.28 mmol), n-butyllithium (3.95 ml, 1.6M in hexane, 6.33 mmol), zinc chloride (0.90 g, 6.61 mmol), compound **286** (2.05 g, 6.00 mmol), tetrakis(triphenylphosphine)palladium(0) (0.2310 g, 0.20 mmol), lithium chloride (0.5269 g, 0.012 mol).

The experimental procedure was as described for the preparation of compound **279**. The crude product was purified by column chromatography [silica gel / petroleum fraction (bp 40-60 °C) - dichloromethane, 5:1] to give a pale-yellow solid which was recrystallised from ethanol-ethyl acetate (2:1) to yield colourless crystals.

Yield 1.37 g (63%); transitions (°C) K 106.5 N 129.0 I; ^{1}H nmr (CDCl$_3$) δ 0.90(3H, t), 1.10(3H, t), 1.30(4H, m), 1.65(4H, m), 2.45(2H, t), 2.65(2H, t), 7.17(2H, d), 7.45(1H, q), 7.48(2H, d), 7.55(1H, q), 7.71(2H, 2xd), 7.87(1H, d), 7.97(1H, d); ir (KCl) ν_{max} 2960, 2940, 2880, 1600, 1515, 1480, 1025, 900, 830 cm^{-1}; ms *m/z* 364(M$^+$), 335, 307, 278.

2.6 Discussion of Synthetic Methods

2.6 (a) Lateral Fluoro-substituted Esters (Schemes 1-9, p 70-78)

In this section of work the aim was to synthesise a series of lateral fluoro-substituted esters, *viz* fluoro-substituted derivatives of 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates (**44-57**), 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxy- benzoates (**59-74**), 4-cyanophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoates (**75-77**), 4-cyanobiphenyl-4'-yl hexanoates (**79** and **80**) and 4-cyanobiphenyl-4'-yl heptoxyethanoate (**82**).

The esters themselves were all prepared by a recently reported method[178] by using *N*,*N*-dicyclohexylcarbodi-imide (DCC) and 4-*N*-pyrrolidinopyridine (catalyst). This is a very convenient, one-pot, process carried out in dry dichloromethane at room temperature and gave excellent yields (see p 122). This method is, for obvious reasons, preferable to others[179,180] which involve the formation of the moisture-sensitive acid chloride as an intermediate.

However, the preparation of the required acids and phenols needed careful planning. The specific substitution patterns in the benzene rings presented many difficulties, particularly for those with four substituents in a single ring. For many such compounds the use of conventional aromatic substitution procedures was impossible.

4,4'-Disubstituted biphenyls (scheme 1, p 70) are extremely difficult to modify by further substitution because all the unsubstituted ring positions are sterically hindered. The possibilities are even more limiting when one ring is activated and the other is deactivated towards further reaction by the 4- and 4'- substituents because reaction, if it does occur, may involve the wrong ring.

These observations apply in the preparation of biphenols **11** and **12**, which, because of the substitution patterns required, were best obtained by coupling two appropriately substituted, one-ring units. Several cross-coupling procedures are available, including $NiCl_2$.dppp catalysed reactions of Grignard reagents with aryl halides,[167] $Pd(PPh_3)_4$[181] and $PdCl_2(PPh_3)_4$[182] catalysed reactions of organo-zinc halides with aryl halides[148] and the $Pd(PPh_3)_4$ catalysed reactions of aryl boronic acids with aryl halides[161-164] (cross-coupling reactions are discussed further in the Introduction, p 56). The last procedure was chosen because the arylboronic acids are easily prepared (in large quantities if required) and can be stored indefinitely to be coupled with different suitable systems when convenient. This cross-coupling reaction reported[161,162] good yields with a lack of homo-coupling, inertness of many functional groups (sterically hindered systems still couple well although longer reaction times are required) and, as the reaction is carried out in benzene and 2M sodium carbonate solution, anhydrous conditions are not required.

The boronic acid (**2**)[175] was prepared by adding the cooled Grignard reagent of compound **1** to a cooled (-78 °C) solution of tri-isopropyl borate in dry THF under dry nitrogen,[170] and the product purified by recrystallisation from water. During this process, an oil separated and it was removed from the mixture (it solidified later) and dried. This solid was identified as the trimeric anhydride of compound **2** and the pure boronic acid **2** crystallised from the water solution. However, since both the pure boronic acid and its trimeric anhydride are equally suitable for the coupling reaction (*e.g.* step 1E, Scheme 1, p 70) susequent boronic acids were not purified (see also p 223).

For the bromination of compound **3**, mild conditions (*N*-bromosuccinimide at low temperature[183]) were used to prevent any bromination in the 6-position, but this was not necessary for the preparation of compound **6** and bromine in acetic acid was used.[184]

The diazotisations-cyanations[185] to give compounds **7** and **8** proved to be difficult and involved procedures which gave moderate, variable yields. It was essential to hold the starting amine in solution and to have accurate temperature control, hence the slight differences in detail between the preparations of compounds **7** and **8**.

Compounds **9** and **10** were prepared by a tetrakis(triphenylphosphine)palladium(0)[181] catalysed cross-coupling reaction[161-164] which is discussed in detail in the Introduction (p 56). For the demethylation[186] of compounds **9** and **10** excess boron tribromide was required due to the presence of the nitrile group. These demethylation reactions were carefully monitored by glc analysis (as were most reactions carried out) and quantitative yields were obtained.

Scheme 2 (p 71) is concerned with the preparation of

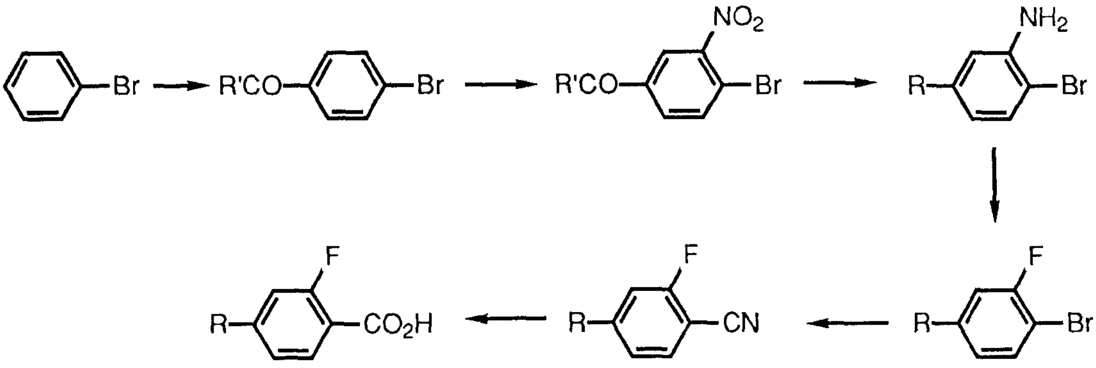
2,6-difluoro-4-hydroxybenzonitrile (**18**), which, if a method for the conversion of ArBr into ArOH in the presence of a nitrile group was available, could have been prepared from compound **8** (see Scheme 1, p 70). However, this was not possible and so a five-step synthesis was undertaken starting with 3,5-difluoroanisole (compound **13**, available from Fluorochem Ltd.). The metallation (with n-butyllithium) of compound **13** was crucial to the success of this scheme (in fact crucial to the whole programme of ester preparations since it is also used in Scheme 4, p 73) because although other methods were sought none were suitable.

It has been reported that anisole and fluorobenzene are lithiated at the *ortho* position[187] and both 3-fluoroanisole and 1,3-difluorobenzene are metallated between the substituents.[187-190] These observations indicate that a methoxy- or a fluoro- substituent both direct metallation to an *ortho* position. However, what cannot be found in the literature is what happens when two competing systems are present in one compound, as in 3,5-difluoroanisole. Is metallation favoured between the methoxy- and fluoro- substituents (two such positions exist in 3, 5-difluoroanisole) or is the position between the two fluorines (only one site) preferred for metallation? The preparation of compound **14** was a decisive test of this choice and the lithiation had to be carried out at -78 °C (or at least ~-60 °C) to avoid the formation of the highly unstable benzyne system *via* the elimination of lithium fluoride; addition of the cold lithium derivative to dry ice in dry ether completed the conversion. In fact, a pure product (compound **14**) was obtained in excellent yield with no trace of impurity and the ^{1}H nmr spectrum of the product was conclusively different from that expected for the other possible acid obtained by metallation at a position between the methoxy- and fluoro- substituents. The conclusion from this result is that two fluorine atoms *ortho* to a hydrogen atom cause greater acidity than one *ortho*-fluorine atom and one *ortho*-methoxy group.

Nitrile **17** was prepared from acid **14** in good overall yield by the usual sequence of reactions (*i.e.* conversion to the acid amide *via* the acid chloride followed by dehydration to the nitrile).[163] Demethylation of compound **17** was completely unsuccessful by the previously used boron tribromide in dry dichloromethane method[186] (see Scheme 1, p 70) despite the use of reflux conditions. This is perhaps due to the strong electron-withdrawing effect of the nitrile and the two fluorine substituents. Successful demethylation in good yield was achieved by a method[180] using aluminium chloride and sodium chloride at 180 °C.

Scheme 3 (p 72) shows the simple preparation of 4-butoxybenzoic acid (compound **20**) and 4-butoxy-2-fluorobenzoic acid (compound **27**). The preparation of 4-pentyl-2-fluorobenzoic acid (compound **24**) was difficult because of the substitution pattern required and epitomizes the often much greater difficulty in obtaining an alkyl-substituted compound than an alkoxy-substituted homologue (*e.g.* compound **27**).

Compound **24** had previously been prepared[191] by the six-step route shown below (Figure 31). However, although innovative, the route was unattractive due to messy reactions and low yields.



One Possible Synthetic Route to Compound **24**

Figure 31

Compound **7** had already been prepared in quantity (see Scheme 1, p 70) and by the use of the nitrile-tolerating alkynylzinc reagent[150] in dry THF with a tetrakis(triphenylphosphine)palladium(0) catalyst,[181] the alkyne **21** was obtained in excellent yield (see also the general discussion of coupling reactions in the Introduction p 56). Then because it was anticipated that hydrogenation of this alkyne may affect the nitrile group, compound **21** was hydrolysed first. The hydroysis should have given compound **22** but the conjugated triple bond was hydrated to give an enol which tautomerised to give 2-fluoro-4-pentanoylbenzoic acid. Compound **21** was therefore hydrogenated, in good yield, with the nitrile group totally unaffected! Subsequent hydrolysis with sulphuric acid and acetic acid[192] gave a good yield of the acid **24**.

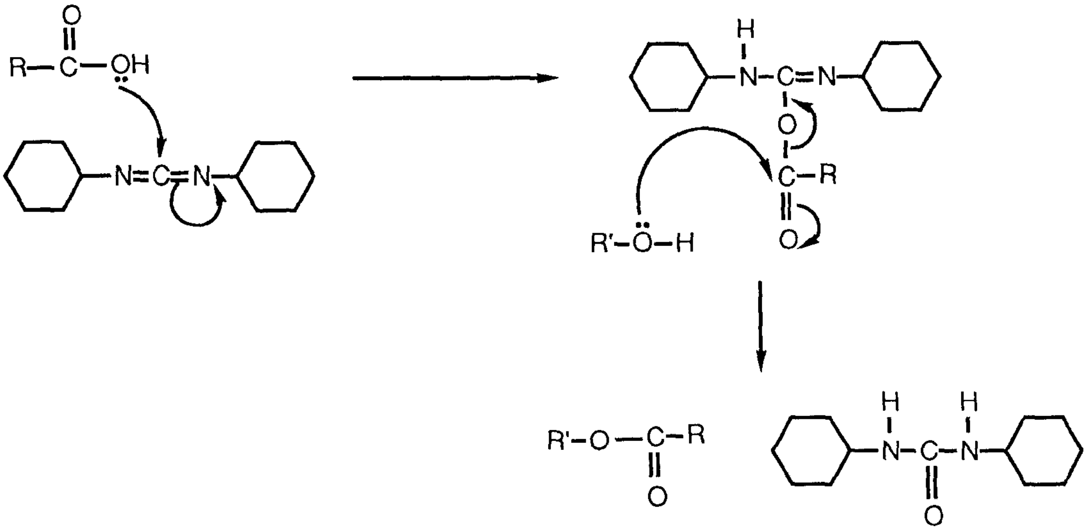
The preparation of the difluoro-substituted acids (compounds **33** and **36**) in scheme 4 (p 73) is based on the metallation between the two fluorine atoms as discussed previously (see p 213). However, although the preparation of the butoxy derivative was straightforward, the synthesis of the pentyl acid (**33**) was hampered by the troublesome preparation of compound **32**. This was due to the failure of several catalysed coupling reactions which according to the literature[127,167,165,193] should have occurred in good yield.

Therefore a three-step sequence of standard reactions which were operationally simple gave a good overall yield of compound **32**. Addition of pentanal to the Grignard reagent of compound **29** gave the benzyl alcohol (**30**) in excellent yield (69% from distillation or 98% from column chromatography). Initially direct hydrogenolysis of the benzyl alcohol (**30**) was attempted, but although several acid catalysts were used, this failed. Hence the use of phosphorus(V) oxide in pentane to obtain the alkene (**31**), which was not isolated; hydrogenation of the filtered solution over 5% Pd/C at room temperature and atmospheric pressure gave compound **32**.

The final acid to be prepared was 4-(*trans*-4-propylcyclohexylethyl)benzoic acid (**41**). The acid chloride (**37**) was supplied by our collaborators, BDH Ltd. and was involved in a normal Friedel-Crafts acylation with bromobenzene to give the ketone **39**. A simple, efficient and mild reduction system of triethylsilane and trifluoroacetic acid[194] was used to give compound **40**. Removal of the bromine with n-butyllithium in dry THF followed by carboxylation with dry ice in dry ether gave an excellent conversion into the acid (**41**).

2-Fluoro-4-hydroxybenzonitrile (**25**), 4-pentylbenzoic acid (**42**) and 4-cyano-4'-hydroxybiphenyl (**58**) were kindly supplied by our collaborators BDH Ltd. Tetrakis(triphenylphosphine)palladium(0) was prepared by a method of Coulson[181] and heptoxyacetic acid (**81**) was kindly given by Dr I. G. Shenouda; all other starting materials are commercially available.

The use of *N,N*-dicyclohexylcarbodi-imide as a condensing agent in ester synthesis has been the subject of several publications.[178,195-198] In 1958 Khorana and coworkers[195] suggested a mechanism similar to that shown in Figure 32. In 1963 Doleschall and Lempert[196] claimed to have proved the mechanism by the synthesis of an intermediate.

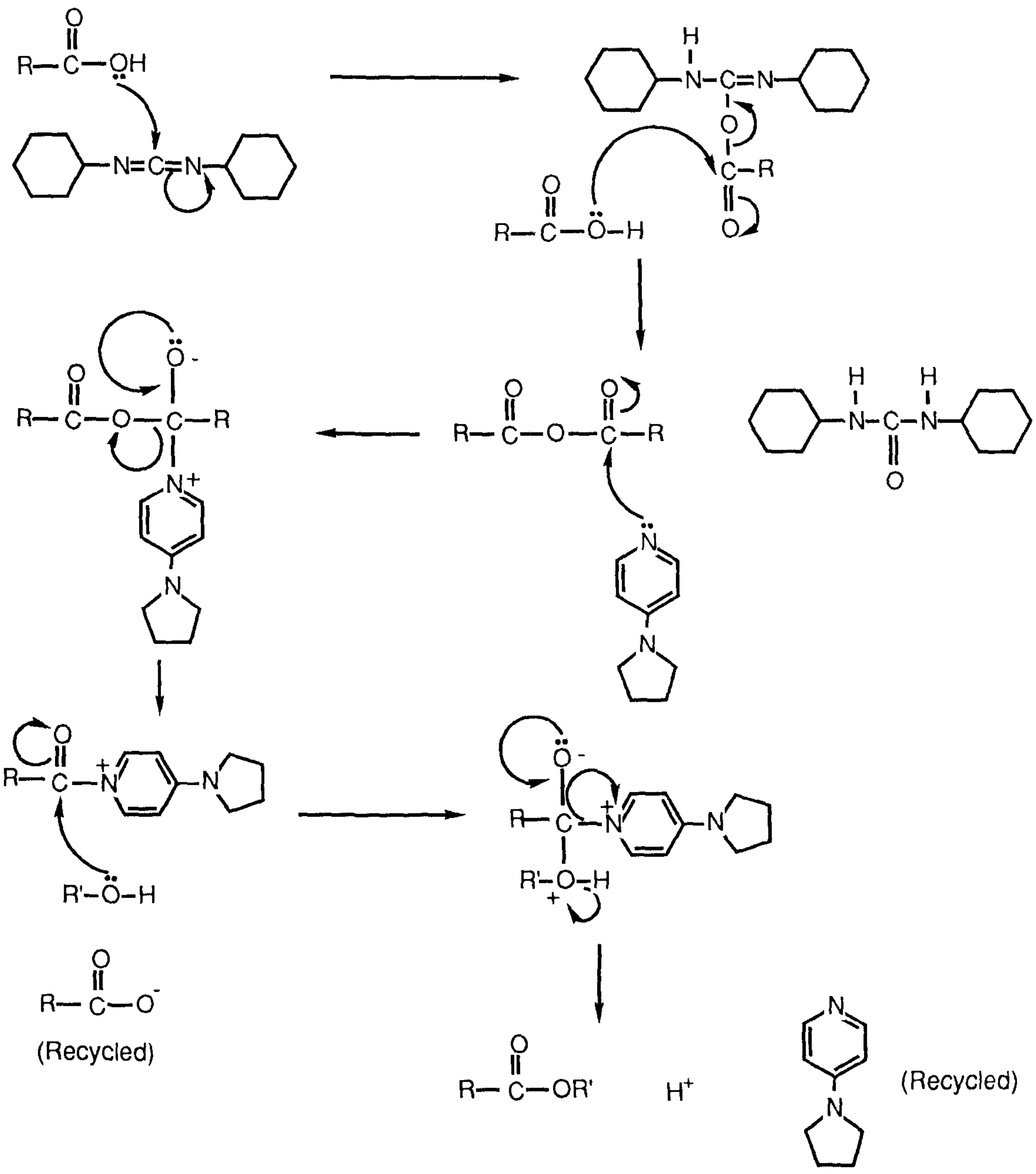


A Suggested Mechanism for Esterification using DCC as a Condensing Agent

Figure 32

In 1978 Hassner and Alexanian[178] reported on the synthesis of esters of both aryl and alkyl carboxylic acids and primary, secondary and tertiary alcohols and phenols. This involved the use of a tertiary aminopyridine catalyst (4-*N*-pyrrolidinopyridine appears to be the most effective). These workers suggested the mechanism shown in Figure 33, which involves the conversion of two moles of acid into the anhydride by means of the *N*,*N*-dicyclohexylcarbodi-imide which is converted into the *N*,*N*'-dicyclohexyl urea. The catalyst then attacks the anhydride and the resultant intermediate is attacked by the alcohol or phenol and the acid produced is recycled. The desired ester is then produced with the regeneration of the catalyst.

Although the latter mechanism is the more recent, it does seem reasonable that both mechanisms will occur and the balance as to which mechanism is more dominant will be determined by the type of acid and hydroxyl (alcoholic or phenolic) compounds being used or by the experimental procedure. If the *N*,*N*-dicyclohexylcarbodi-imide (DCC) is added all at once to the solution containing the acid then probably all the acid will react with all the



A Suggested Mechanism for Esterification Proceeding *via* a Symmetrical Anhydride

Figure 33

DCC, this leaves no further acid from which to form the anhydride and product formation will occur *via* the first mechanism (Figure 32). If the DCC is added slowly to the mixture then the second mechanism (Figure 33) may well be more dominant since anhydride formation will be possible and this experimental procedure certainly leads to slower reaction times.[199] It also seems reasonable that if the hydroxyl compound is unreactive, for example if sterically hindered acids are used then only the second mechanism (Figure 33) is applicable and the symmetrical anhydride will be isolated and not the desired ester.

In the second mechanism (Figure 33), the catalyst plays an active role by being involved in the formation of an intermediate; however, the catalyst plays no such part in the first mechanism and presumably acts as a proton carrier. In the absence of the catalyst very low (~10%) yields of the desired ester are obtained; in the absence of DCC no esterification occurs. All esters prepared in this thesis were left overnight and overall yields were excellent (~90%) after column chromatography and any low yields were accounted for by losses on recrystallisation since several of the two ring esters (compounds **44-57**) were quite soluble in ethanol.

2.6 (b) Lateral Monofluoro- and Difluoro- substituted Terphenyls and Biphenyls

(Schemes 10-26, p 79-95)

This discussion covers the synthesis of a series of 1,1':4',1'' terphenyls with alkyl or alkoxy chains substituted at the 4 and 4'' positions without lateral substituents, and with one, two, three and four lateral fluoro-substituents. Also discussed is the preparation of several 4,4'-alkoxy-alkyl- and dialkyl- biphenyls with 2,3-difluoro-substituents.

The basis of all the preparations is the tetrakis(triphenylphosphine)palladium(0)[181] catalysed cross-coupling reaction of arylboronic acids with aryl halides[161-164] (see also general discussion of cross-coupling reactions in the Introduction, p 56). As explained in section 2.6 (a), p 211, the further modification of a biphenyl unit (and even more so for a terphenyl unit) is very difficult, and almost impossible when specific substitution patterns are required. So small, appropriately substituted units are prepared, one being an arylboronic acid system, the other being an aryl halide (bromide or iodide). The coupling reaction of these two units gave the desired products in usually excellent yield. Sometimes a lower yield was obtained because of a difficult separation during column chromatography (but usually the crude product was very clean and very easily purified by column chromatography) and/or because of a low return from the recrystallisation (especially for low melting derivatives).

Scheme 10 (p 79) shows the preparation of the simple, most frequently used 1-alkyl(or alkoxy)-4-bromobenzene units (**84, 85** and **91-93**). These were then converted into the appropriate boronic acids by adding the cooled Grignard reagent to a cooled (-78 °C) solution of tri-isopropyl borate in dry THF under dry nitrogen.[170] Complete reaction at the Grignard stage is, of course, desirable (monitored by glc analysis) since any unconverted aryl bromide will react with the boronic acid in any future coupling reaction. Compound **95** was supplied by our collaborators BDH Ltd.

In scheme 11 (p 80) the first two terphenyls prepared could have been synthesised by using the boronic acid of the biphenyl unit and the 1-alkoxy-4-bromobenzenes but biphenylboronic acids are less easily prepared than single ring derivatives and are less easy to deal with (especially true of the 4'-alkoxybiphenyl-4-ylboronic acids which are very insoluble and their Grignard reagent precursors are difficult to form). This opportunity for an alternative preparation, as described above, often arose and it was resolved by choosing the boronic acid which was more easily prepared or more readily available to couple to the appropriate aryl bromide.

Since compounds **102, 103, 107** and **108** have a common pentylbiphenyl section then it was sensible to make a larger quantity of one boronic acid (compound **96**) and couple this to several aryl bromides rather than make four separate boronic acids. An additional reason was that to make the boronic acids of compounds **105** and **106** (see compound **135**, Scheme 15, p 84) the lithium derivative would have to be prepared and used at low temperature (<-60 °C) because at the high temperatures required to form the Grignard reagent the *ortho*-fluorine atom would eliminate to form a benzyne.[187] Compounds **107** and **108** were prepared as a Part II, Third Year Undergraduate Project (1988) by Miss H. Giddings (see also p 230).

The ease of preparing compounds **110, 111** and **112** (Scheme 12, p 81) is due to the three boronic acids (**94, 86** and **87**) being prepared in large quantites (for general use) and the availability of compound **109** from our collaborators BDH Ltd. (also compounds **117** and **118**)

The preparation of compound **115** was originally attempted by metallating the iodo site of compound **113** with n-butyllithium, adding pentanal, dehydrating the alcohol (phosphorus(V) oxide) and hydrogenating the resulting alkene using 5% Pd/C. However, in the hydrogenation, the compound was also debrominated to a large extent and a much better, more direct method was tried. This involved an alkynylzinc coupling reaction[150] to compound **113**; (see also Scheme 3, p 72 and also p 232) at room temperature coupling only occurs at the iodine site to give compound **114** in excellent yield. The problem of debromination during hydrogenation was overcome by using PtO_2 in ethanol[200] which gave a clean, efficient conversion to compound **115** (compound **114** is also used in Scheme 35, p 104). Compound **116** was simply prepared as for compounds **86, 89** and **94** (see p 218).

Scheme 13 (p 82) represents the first work leading to the synthesis of difluoroterphenyls. The bromination of compound **122** was carried out in excellent yield as described previously (see Scheme 1, p 70), however, the homolytic aromatic substitution using isopentylnitrite in excess dry benzene[201,202] gave a low yield of material which was difficult to purify. A Friedel-Crafts acylation and subsequent reduction by triethylsilane-trifluoroacetic acid[194] (a mild, selective method which avoids the basic conditions of the Wolff-Kishner reaction which can cause the loss of fluorine atoms from aromatic systems such as compound **125**) gave compound **126**. The reaction sequence leading to compound **126** was carried out by Mr N.J. Thompson as a Part II, Third Year Undergraduate Project (1987). The subsequent coupling reactions were carried out in the usual way (section 2.6 (a), p 211 and Introduction, p 56) to give yields of 82% and 73% respectively for pure compounds **127** and **128** (poor returns from the recrystallisations reduced the respective yields to 55% and 47%).

So far all boronic acids have been prepared by metallation (either by the Grignard reagent or the lithium derivative) of a bromine site followed by the addition of tri-isopropyl borate. However a boronic acid can also be prepared from a lithium derivative where the n-butyllithium has removed an acidic proton. This lithiation procedure was carried out at -78 °C (or at least below ~-60 °C) to prevent the loss of lithium fluoride and the formation of the highly unstable benzyne derivative.[187] Such an acidic proton is found in compound **32** (see Scheme 14, p 83; see also Scheme 4, p 73) between the two fluorine atoms. This acidity is due to the high electronegativity of the two fluorine atoms stabilising the resulting anion. Such an acidic proton was utilised in schemes 2 and 4 to provide benzoic acids (see Section 2.6 (a), p 213).

The coupling reactions involving boronic acids where the boronic acid group is between two fluorine atoms were very poor indeed and compounds **130** and **131** were produced in very poor yields. A small amount of homo-coupled product (*i.e.* quaterphenyls formed by the homo-coupling of compounds **95** and **117** respectively) was detected in each case and a significant quantity of compound **32** was isolated. It therefore seems that the 2,6-difluoroboronic acid (**129**) decomposed in the coupling reaction (but not before a small amount of cross-coupling had occurred) and the lack of boronic acid available to cross-couple with the aryl bromides **95** and **117** led to the slight homo-coupling of these bromides.

The cross-coupling of the 2,6-difluorobiphenylboronic acid (**133**) with compound **91** was very similar to those described above except that no desired product was formed in this case. A quantitative yield of the precursor to the boronic acid was isolated (*i.e.* compound **132**), but no homo-coupled product was detected in this case.

The evidence from these three reactions leads to the conclusion that 2,6-difluoro-substituted arylboronic acids are hydrodeboronated under the conditions used in a cross-coupling reaction because, although a slight trace of such boronic acid precursor material in the boronic acid is unavoidable (because the boronic acids were not purified), it is certain from the spectral data and solid nature of boronic acid **129** that no detectable quantity of liquid precursor **32** is present. However, the boronic acid **133** was clearly contaminated with its precursor material (the preparation of this boronic acid was probably impaired by its poor solubility in dry THF at -78 °C) but this small amount (not more than 5% from the ^{1}H nmr spectrum) does not account for the quantitative return after the attempted coupling reaction. The subsequent absence of any cross-coupling can lead to a homocoupled product (the usual lack of homo-coupling is an attractive feature of the boronic acid cross-coupling method).

Scheme 15 (p 84) highlights fully the dilemma of which component should be converted into a boronic acid and which should be left as the aryl bromide. The first terphenyl (compound **136**) was prepared in low yield from the coupling of boronic acid **135** [which had to be prepared using n-butyllithium at -78 °C (see also 213 and p 220) to prevent the formation of the benzyne derivative[187]] to compound **109**. The reason for this low yield is because the presence of the quaterphenyl (from the homo-coupling of compound **109**) in the crude product led to a difficult separation on column chromatography and the recrystallisation gave a poor return.

The low yield for the hexoxy derivative (compound **136**) prompted the preparation of the octoxy homologue (compound **138**) the other way round. *i.e.* to make the boronic acid of the biphenyl moiety and couple this in the usual way to the single ring aryl bromide (compound **106**). No homo-coupled product was formed and a good yield of the desired product (compound **138**) was obtained.

The availability of this biphenylboronic acid (compound **137**) facilitated the preparation of two further difluoro-substituted terphenyls (compounds **139** and **140**). No homo-coupling was detected in these two coupling reactions (or in any coupling reactions discussed later) and good yields of the desired products were isolated.

Scheme 16 (p 85) begins the preparation of a large and comprehensive set of *ortho*-difluoro-substituted terphenyls and biphenyls. All such *ortho*-difluoro-substituted systems were originally prepared from 1,2-difluorobenzene (compound **141**).

Schemes 16 and 17 show the eventual synthesis of terphenyls with the two *ortho*-fluorines in the centre ring. 1,2-Difluorobenzene has two protons *ortho* to a fluorine atom. These two protons are equivalent and because of the electron withdrawing effect of the *ortho* fluorine atoms they are acidic.[187] Treatment of 1,2-difluorobenzene with 1 mol equivalent of n-butyllithium in dry THF under dry nitrogen at -78 °C and subsequent stirring for 2.5 h gave the mono-lithium derivative (2.5 h is probably longer than is needed). Treatment of the lithium derivative with tri-isopropyl borate in dry THF at -78 °C and allowing to warm to room temperature gave the borate ester which on stirring with 10% hydrochloric acid at room temperature yielded the boronic acid. It is worth re-emphasising that usually the boronic acid appears (from the spectral data) to be a mixture of the acid and its dimeric, trimeric and perhaps polymeric anhydrides (the proton nmr spectra are not at all clear with broad signals), the crude mixture can be used in the subsequent coupling reaction because the basic conditions (aqueous sodium carbonate) hydrolyse these anhydrides. Also present in the crude boronic acid mixture is a slight trace of the precursor due to incomplete lithiation and/or the presence of a trace of moisture. This impurity does not interfere in the coupling stage and was removed by column chromatography or as a last resort by the final recrystallisation (or Kugelrohr distillation in the case of *ortho*-difluoro-substituted biphenyls). In one case during subsequent work, where a substantial amount of this type of impurity was identified, the impurity was successfully removed by extracting the boronic acid into 2M-potassium hydroxide and washing the impurity out with ether; in retrospect it seems that all boronic acids should have been so purified. However, using the purified *ortho*-difluoro-substituted boronic acids in cross-coupling reactions is not completely satisfactory as hydrodeboronated material arising during the reaction is found in the crude product. This evidence (and the quantitative hydrodeboronation achieved by the use of reflux conditions in just benzene and aqueous 2M-sodium carbonate) proves that hydrodeboronation of this type of boronic acid does occur in the conditions used in the cross-coupling reaction but this does not prevent complete reaction and excellent yields of the desired cross-coupled product (except, of course, where the boronic acid group is between two fluoro-substituents; discussed on p 221). More recent work has indicated that simple boronic acids (*i.e.* those with no *ortho*-fluoro-substituents) are also hydrodeboronated during the coupling reactions but again this does not prevent complete reaction and excellent yields from being obtained

Boronic acid **142** was coupled with aryl bromides **91** and **93** to give biphenyl systems **143** and **144** in excellent yields. These biphenyls have an acidic proton which can be utilised as above to obtain biphenylboronic acids; subsequent coupling with the same or a different aryl bromide gave a selection of terphenyl systems (compounds **147-152**, Scheme 17, p 86) all in excellent yield (except where poor recrystallisation return has reduced the yield).

2,3-Difluorophenylboronic acid (**142**) was (see scheme 18, p 87) oxidised[203,204] with 10% hydrogen peroxide in ether to the phenol **153**. Alkylation of this phenol in the usual, simple way gave the alkoxy-substituted units (compounds **154** and **155**). Both these compounds have an acidic proton and treatment as described previously (p 222) gave boronic acids (compounds **156** and **157**). These boronic acids were then coupled in the usual way to biphenyl bromides (compounds **95** and **158**, supplied by our collaborators BDH Ltd.) to give excellent yields of the *ortho*-difluoro-substituted terphenyls (compounds **159-161**, the *ortho*-difluoro-substituents are in an alkoxy-substituted end ring). The boronic acid **157** was also coupled to phenyl bromides **91** and **92** to give *ortho*-difluoro-substituted biphenyls **191** and **192** (see scheme 22, p 91). These biphenyls were purified by column chromatography and because of their low melting nature, were not recrystallised but were distilled at 0.1 mmHg using a Kugelrohr apparatus.

The route to terphenyls with two *ortho*-fluorine atoms in an alkyl-substituted end ring (scheme 19, p 88) was more complicated. However, the basis behind the formation of compounds **168-170** is similar to that described for the preparation of compound **32** in scheme 4 (see p 73 and p 215). The aldehyde was however added to the lithium derivative at low temperatures (<-60 °C); the use of phosphorus(V) oxide in pentane to dehydrate the alcohol followed by hydrogenation of the filtrate at room temperature and atmospheric pressure over 5% Pd/C gave a very efficient overall conversion of 1,2-difluorobenzene into 1-alkyl-2,3-difluorobenzenes (compounds **168-170**). From this point, treatment in the same way as the 1-alkoxy-2,3-difluorobenzenes (see Scheme 18, p 87) to give the boronic acids and subsequent coupling gave *ortho*-difluoro-substituted terphenyls with the two fluorine atoms in an alkyl-substituted end ring (compounds **175-181**) and biphenyls **193-195** (see scheme 22, p 91).

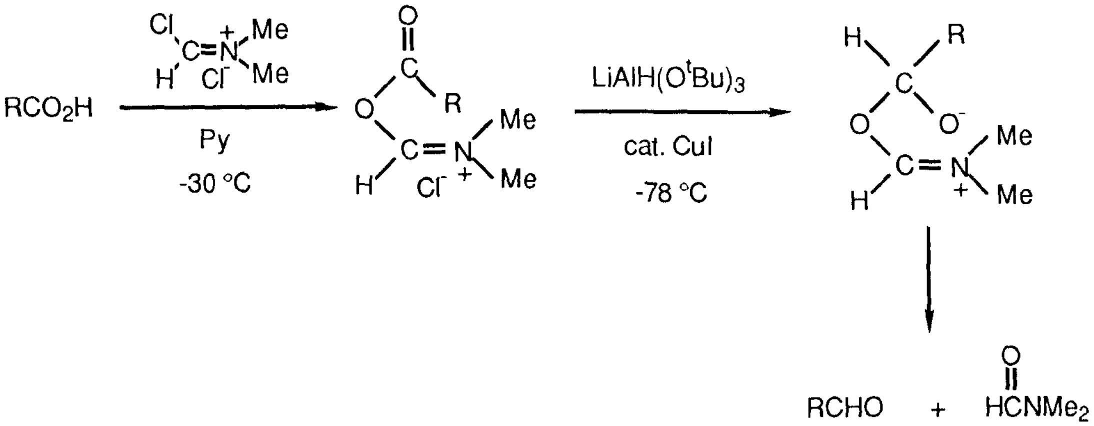
Scheme 20 (p 89) shows that it is possible to selectively couple a boronic acid to 1-bromo-4-iodobenzene at the iodo site. Two products are produced (evidence provided by gc/ms analysis), the first being the desired bromobiphenyl unit (compound **185**) and a terphenyl produced by double coupling. The other possible biphenyl product, that is the product from coupling at the bromo site [4-iodo-4'-(4-methylhexyl)biphenyl] was not produced at all, probably because the iodo site in that compound is so reactive that it would be quickly converted into the terphenyl. The selective coupling reaction was carefully monitored by glc analysis to achieve optimum conversion into the desired product and the product was isolated in good yield by column chromatography. Further coupling of this compound with the appropriate boronic acid (**171** or **157**) gave good yields of the two *ortho*-difluoro-substituted terphenyls (**186** and **187**). Such a selective coupling at the iodo site, although remarkably good, did involve some competition at the bromo site which requires careful separation (by column chromatography) of the desired compound from some starting material and terphenyl present in the crude final mixture. This can easily be overcome by the coupling of an arylboronic acid (*e.g.* compound **183**) to 4-bromoanisole followed by the demethylation of the biphenyl product to give a biphenol. It has recently been discovered by the author (from work not included in this thesis) that aryl triflate[157,158,168,205] derivatives will couple to arylboronic acids under similar conditions used for aryl bromides[161-164] in similarly excellent yields (see Introduction, p 56). Therefore, if the triflate derivative of the above biphenol is prepared it will be possible to couple this to a different arylboronic acid (*e.g.* compounds **171** and**157**). This method using the triflate derivative does involve more steps but does offer total selectivity. It is highly likely that the ambivalent selective coupling to an aryl bromo-iodo- unit will, in some cases, give mixtures of compounds which are impossible to separate; the total selectivity offered by the novel triflate method will produce better yields of purer compounds.

A trifluoro-substituted terphenyl (compound **188**) was prepared in good yield by a coupling reaction between two previously prepared units (see scheme 21, p 90) and this was followed by the preparation of a tetrafluoro-substituted terphenyl (compound **190**) which involved another selective coupling reaction (similar to that described above; also note the possibility of an alternative triflate coupling) to give an *ortho*-difluoro-substituted biphenyl bromide **189** which was coupled with a different boronic acid (**171**) to give the desired tetrafluoro-substituted terphenyl (**190**).

Schemes 23-26 (p 92-95) detail the preparation of four compounds which are *ortho*-difluoro-substituted biphenyl systems with 4- and 4'- alkoxy- or alkyl- substituents, where a *trans*-substituted cyclohexane ring forms part of the alkoxy- or alkyl- substituent.

The synthesis of compound **199** was relatively straightforward as the dimethylene-linked cyclohexylbromobenzene (**198**) was prepared in a similar manner to the straight chain alkyl bromobenzenes (see scheme 10, p 79). Friedel-Crafts acylation of bromobenzene (**38**) with the acid chloride (**196**) (supplied by BDH Ltd.) gave the ketone (**197**) which was reduced to the desired dimethylene-linked cyclohexyl system by using the mild triethylsilane-trifluoroacetic acid method;[194] the usual coupling reaction gave the desired *ortho*-difluoro-substituted system (compound **199**).

To obtain the isomer of this compound with the fluorines in the centre ring (*i.e.* with the aromatic ring also substituted by the cyclohexyl-substituent) proved more difficult. To obtain compound **203** by the usual method (see Scheme 19, p 88) required the appropriate aldehyde (**201**). Both the acid (compound **200**) and the acid chloride (compound **196**, see above) were available from our collaborators BDH Ltd. The more usual route to aldehydes is by the reduction of the acid chloride,[206,207] but yields are often poor, especially for aliphatic systems. A method of reducing the acid to the aldehyde was recently reported[208] (Figure 34) which appears rather complicated but is operationally straightforward and gave an excellent yield of the desired aldehyde (compound **201**).



Mechanism for the Reduction of Carboxylic acids to Aldehydes

Figure 34

This procedure is remarkable because usually acids are difficult to reduce and any reagent capable of reducing the acid would normally reduce the aldehyde straight to the alcohol. The alcohol **202** was prepared in the same manner as described previously (see p

224). However, instead of the previously used procedure of dehydration followed by hydrogenation it was decided to attempt a one step reduction using the triethylsilane and trifluoroacetic acid method[194] (usually used to reduce ketones). This reaction was carried out as usual and glc analysis revealed a complete reaction, however, after an attempt to purify by distillation had failed (every component distilled over), glc analysis revealed the presence of alcohol (compound **202**). Purification by column chromatography gave a low yield of the desired product and a substantial amount of the alcohol. The recovered alcohol was then treated to the usual dehydration (phosphorus(V) oxide) and hydrogenation (5% Pd/C) with a very good yield of the reduced product. The reason for the failure of the triethylsilane and trifluoroacetic acid method was perhaps due to the formation of an ester with the trifluoroacetic acid (which prevented reduction) which reversed during the distillation to give back the starting alcohol.

Schemes 25 and 26 show the synthesis of compounds similar to the two just discussed but both are methoxy linked cyclohexyl systems with a *trans*-4-heptyl-substituent whereas compounds **199** and **205** have a *trans*-4-pentylcyclohexylethyl-substituted moiety.

The preparation of the bromide (**207**) from the alcohol (compound **206**, supplied by BDH Ltd.) represents a standard procedure reported to give a high yield.[209,210] However, despite many attempts, constant monitoring by glc analysis revealed a maximum of 80% conversion and separation of the product from the starting material by distillation proved impossible. What is most interesting is that a sample produced previously proved by glc analysis to be a 1:1 mixture of starting material to product; this indicates the benefits of glc analysis to monitor the progress of reactions. Although not ideal, the crude bromide (80% pure) was used to alkylate both 4-bromophenol (**83**) and 2,3-difluorophenol (**153**) as the impurity was allowed for and the appropriate excess of material was added. Both these alkylation reactions failed when carried out in butanone but when repeated with cyclohexanone as the solvent a complete reaction was achieved (glc analysis).

The process of making the boronic acid from compound **210** in the usual way failed; this was half-expected since compound **210** was a solid and insoluble in dry THF at

-78 °C. The bromination of compound **210** was, however, straightforward and glc analysis revealed a complete reaction and the formation of a single product. The lack of bromination in the position *ortho* to the cyclohexyl-substituent is probably due to steric hindrance and it would be useful to attempt bromination of both the straight chain homologues (*e.g.* compounds **154** and **168**) as an alternative to low temperature lithiation for making the boronic acid [the boronic acid of the unfluorinated moiety could be prepared at room temperature (*via* the Grignard reagent), low temperature here is not critical although yields are not as good]. This could provide a more suitable method when working on a large, industrial scale.

Both coupling reactions in these schemes (25 and 26) were by the usual procedure and produced the usual good yields.

2.6 (c) Lateral Cyano- and Trifluoromethyl- substituted Terphenyls (Schemes 27-32, p 96-101)

The major method of preparing a terphenyl, as used in this work, is to couple a biphenyl system with a phenyl system; another way is to couple a phenyl system twice (two mol equivalents) in the same reaction with another phenyl system.

The latter approach was used here because the preparation of 2,5-dibromobenzonitrile (**215**, Scheme 27, p 96) was described in the literature[176] and was easier, in the first instance, to make than a suitable biphenyl system. Compound **215** was prepared by a 'swamping-catalyst' method[176] (large excess of aluminium chloride) in the absence of a solvent. The first bromine to substitute is directed by the nitrile group, as expected, to the 3-position, but the second bromination occurs at a position *para* to the bromo-substituent (*i.e.* the orientation of the second substitution is dominated by the first bromo-substituent).

This compound (**215**) was then coupled in the usual way to give terphenyls (compounds **216** and **217**) in good yields by using double the normal amounts of the appropriate boronic acid and catalyst. The obvious limitation to this coupling method is that the terphenyl products can only have identical end-group substituents (compounds **216** and **217**).

The possibility that one bromo-substituent in compound **215** may be sufficiently more reactive to coupling than the other was investigated with the hope of providing a means to lateral cyano-substituted terphenyls with different end-group substituents. However, careful glc analysis of such a reaction revealed the formation of both possible biphenyl products and the terphenyl product from double coupling with starting material. Purification by column chromatography gave two mixtures; the first fraction consisted of starting material and compound **218**, the second fraction was a mixture of the other possible isomer of compound **218** and the terphenyl. The removal of the starting material from the first mixture by Kugelrohr distillation left just enough pure material (compound **218**) to couple again (to compound **86**) and enable the synthesis, in good yield, of the unsymmetrical terphenyl **219**.

It was obvious that a better method for synthesising unsymmetrical terphenyls such as compound **219** was required. The best way of doing this seemed (at the time) to be to make a bromo-iodobenzonitrile unit (Scheme 28, p 97). Such a compound was prepared by bromination of anthranilonitrile (2-aminobenzonitrile, compound **220**) with *N*-bromosuccinimide which gave a near quantitative yield of compound **221** and subsequent diazotisation/iodination gave a very efficient preparation of the vital unit (compound **222**).

The selective coupling reactions of this compound (**222**) with boronic acids **94**, **86** and **87** worked very well. The normal coupling conditions were used and the reaction was carefully monitored by glc and tlc analysis and the reaction was worked up when the small amount of residual starting material was no longer being used up (usually around 2 h). The crude material contained the desired product with small amounts of starting material and terphenyl from double coupling. Careful purification by column chromatography was required to give remarkably good yields of the desired biphenyl compounds **218**, **223** and **224**. A method offering total selectivity would perhaps be to prepare 5-bromo-2-methoxybenzonitrile (compare with compounds **231** and **232**) and couple this with a phenylboronic acid. The demethylation of the biphenyl product, followed by the preparation of the triflate derivative would enable another coupling with a different phenylboronic acid at the triflate site to give the desired unsymmetrical terphenyl. This possibility of a totally selective coupling is discussed fully on p 225 as part of the *ortho*-difluoro-substituted terphenyls and was discovered whilst working on the coupling of terminal alkynylzinc chlorides to aryl triflate derivatives (see p 234). This type of selective coupling would again involve more steps but it is a much cleaner process and will almost certainly find many widespread synthetic applications in the future.

At this stage it is appropriate to discuss the identification of compound **218**. When compound **218** was prepared by the first method (*i.e.* selective coupling to compound **215**) it was uncertain which possible isomer had been isolated. Both the ^{13}C and ^{1}H nmr spectra would be expected to be little different for either isomer but, with the expert help of Dr D.F. Ewing, the effects of functional groups on shift values were calculated and the correct structure of compound **218** was confirmed. This was, of course, verified by the unambiguous preparation of the compound (**218**) by the second method.

The bromobiphenyl compounds prepared (**218**, **223** and **224**) were used in further coupling reactions to produce three more lateral cyano-substituted terphenyls (compounds **225-227**).

Scheme 30 (p 99) continues the theme of lateral cyano-substituted terphenyls, however the aim here was to have the cyano-substituent on the edge of the aromatic core *ortho* to a terminal alkoxy group. The preparation of the appropriate 2-alkoxy-5-bromobenzonitrile units may have been a problem but surprisingly the brominations of compounds **229** and **230** produced the desired products (**231** and **232**) cleanly and efficiently (glc analysis revealed the absence of any mono-brominated product *ortho* to the alkoxy-substituent or any di-brominated material, despite the use of excess bromine).

The boronic acid species in the subsequent coupling reactions had to be the biphenyl unit (compound **96**) because the boronic acids of compounds **231** and **232** would be difficult to make as the intermediate lithium or Grignard reagent would react with the nitrile group.

The first lateral cyano-fluoro-substituted terphenyl (compound **235**) prepared in scheme 31 (p 100) was simply a coupling of two units (compounds **232** and **137**) which had previously been prepared for other uses. The rest of scheme 31 was carried out by Miss H. Giddings as a Part II Third Year Research Project (1988). It was explained previously (see p 213) that a proton between a fluorine atom and a methoxy group is acidic. In this case the acidic proton is part of a large, very insoluble terphenyl unit (see Scheme 11, p 80) so removal of this proton with n-butyllithium at -78 °C was expected to be a problem. Fortunately lithiation did occur to some extent as tlc analysis of the product revealed the presence of both starting material and what was consistent with acid products (compounds **236** and **237**) and it was decided in each case to leave the removal of the starting material impurity until the final stage. The acids (**236** and **237**) were converted into the respective nitriles in the usual efficient way *via* the acid chlorides (**238** and **239**) and the acid amides[163] (**240** and **241**). The final purification of the nitriles was very simple by column chromatography with some starting material also recovered; overall yields of around 15% (ignoring the recovered starting material) based on the starting lateral fluoro-substituted terphenyls (**107** and **108**) were, however, not good.

Scheme 32 shows how what has already been stated about the selective coupling for the lateral cyano-substituted terphenyls can be applied to lateral trifluoromethyl-substituted systems.

2.6 (d) 2,6-Disubstituted Naphthalenes (Schemes 33-37, p 102-106)

This section discusses the synthesis of 2,6-disubstituted naphthalene compounds including conjugated ethynyl (acetylene or tolane) groups.

One difficulty in the synthesis of such compounds (in comparison to the previously discussed systems) is that the only commercially available 2,6-disubstituted naphthalene starting material is 6-bromonaphth-2-ol. In the first instance this restricts one substituent to an alkoxy-group, leaving the bromo-substituent as the site for the coupling of the ethynylic systems (see schemes 33-35).

All the compounds prepared in this section included 2,6-naphthalene systems and

1,4-benzene systems linked by an ethynyl group (except compound **254**). Compound **254** was prepared in the first instance due to ease of synthesis by the boronic acid coupling method (79% yield). Compound **254** was previously prepared by Zollinger *et al.*[177,211] using the zinc coupling method in 62% yield with identical transition temperatures. It was decided to make a terminal ethyne of one aromatic unit and couple this to the other aromatic unit. The coupling reaction involved making the zinc derivative of the terminal alkyne and coupling this to an aromatic iodide or an activated bromide[150] (*e.g.* 4-bromobenzonitrile, compound **253**) with a tetrakis(triphenylphosphine)palladium(0)[181] catalyst at room temperature in dry THF under dry nitrogen (see also scheme 3, p 72). Another, similar method of coupling developed by Sonogashira *et al.*[169] (also used by Tilley and Zawoiski[200]) is available which avoids the need to make the zinc derivative. However, since the zinc derivative method[150] is a straightforward procedure (the paper also includes the procedure used to prepare terminal alkynes without the need for protecting groups) and was producing good yields; the use of this method was continued.

In scheme 33 (p 102) the terminal alkyne had to be part of the naphthalene system as n-butyllithium is used (to prepare the zinc derivative) which would have affected the nitrile group of the other aromatic system (compound **253**). Since compounds **250** and **251** are non-activated aromatic bromides, the prior conversion into iodides was required. A simple method[212,213] was found which gave excellent near quantitative yields of the iodo-substituted compounds (**255** and **256**); if the reaction was continued for too long then small amounts of dehalogenated material was detected by glc analysis (confirmed by gc/ms analysis). Two methods were used for the conversion of compounds **255** and **256** into terminal alkynes. The first involved the coupling of propargyl alcohol to the appropriate aromatic iodide in the presence of tetrakis(triphenylphosphine)palladium(0)[181] and copper(I) iodide followed by the removal of the -CH_2OH protecting group with alkaline manganese dioxide.[214] The initial coupling reaction appeared to work (glc analysis revealed a complete reaction) but the deprotection conditions (reflux) did not yield the desired terminal alkyne. The second attempt involved the use of lithium acetylide ethylenediamine complex and is based on the paper by Negishi and King[150] (see p 232).

The zinc derivative of this complex is prepared and this is coupled to an aromatic iodide as described previously (see p 214). This procedure gave quite good yields (variable up to 80%) of column chromatographically-purified **257** and **258** (in some cases material from the coupling of the product with the starting material was isolated). The final compounds in scheme 34 (p 103) provided the opportunity to make the terminal alkynes of simple phenyl systems (compounds **263** and **266**) which were more easily isolated by distillation. Another method for the synthesis of terminal alkynes involves the coupling of trimethylsilylacetylene to the appropriate aryl halide followed by a mild (methanolic potassium hydroxide at room temperature) deprotection process.[200,215]

At this stage it was understood from Negishi *et al.*[150] that only aromatic iodides or activated aromatic bromides (*e.g.* 4-bromobenzonitrile) couple with alkynylzinc reagents, so compounds **267** and **268** were prepared using an aromatic iodide (compound **256**). However, although this process of using the iodide was completely satisfactory, the iodide had to be made from the bromide. So in preparing compound **269** it was discovered that alkynylzinc reagents do in fact couple just as efficiently to 'normal' aromatic bromides by the same process as iodides except that reflux conditions are required (in fact monitoring the reaction by glc analysis reveals that such reactions with aromatic bromides take less time and come to completion much easier than for aromatic iodides at room temperature).

This can be considered a good breakthrough because not only does this mean that more easily available aromatic bromides can be coupled to alkynylzinc reagents but selective couplings should also be possible with 100% selectivity (unlike the selectivity of boronic acids with aromatic iodo-bromo-substituted compounds) for alkynylzinc reagents with aromatic iodo-bromo-substituted compounds.

Scheme 35 (p 104) shows that this was the case, a room temperature coupling of pent-1-ynylzinc chloride with 1-bromo-4-iodobenzene (compound **184**) gave a very good yield of compound **270**. This compound was then coupled to the zinc derivative of compound **258** at elevated temperature (~67 °C) to give an excellent yield of the final compound (**271**). Also compound **272** was prepared by a similar selective coupling reaction (see Scheme 12 for the preparation of compound **114**).

If terminal alkynes could have been prepared from aromatic bromides then this again would have been beneficial. However, the attempt to prepare compound **275** from compound **270** using the zinc derivative of lithium acetylide ethylenediamine complex at elevated temperature failed. What occurred was the coupling of the terminal alkyne as it was formed to the aromatic bromide starting material to give a good isolated yield of 1,2-di-(4-pent-1-ynylphenyl)ethyne.

In order to provide a wider range of 2,6-disubstituted naphthalenes with ethynyl linkages from the available precursor (6-bromonaphth-2-ol) a method to couple something at the naphtholic (Ar-OH) site other than a simple alkylation was required. A recent method[205] is suitable which involves the preparation of the triflate (trifluoromethylsulphonate) derivative of the phenol or naphthol by treating the phenol with *N*-phenyltriflamide in triethylamine and dichloromethane at -78 °C under dry nitrogen (an equally suitable and much less expensive method[157,158] has recently been tried by the author, although not covered in this thesis, which uses trifluoromethanesulphonic acid anhydride in pyridine at 0 °C). The triflate derivatives, in a similar manner to aromatic iodides and bromides, can then be coupled to alkynylzinc reagents.[168] Elevated temperatures are required and the presence of lithium chloride in three equivalents is essential for coupling to occur[157,158,168] (see also Introduction on coupling reactions p 56).

Schemes 36 and 37 (p 105 and 106) cover those reactions involving triflate derivatives. Compound **250** was cyanated in good yield with cuprous cyanide[180] and the product was then demethylated in quantitative yield by the well-used boron tribromide method.[186] The triflate derivative (compound **278**) was prepared as generally described above and purified by column chromatography in excellent yield, then, also as described above, it was coupled to the zinc derivatives of compounds **263** and **266**. Excellent yields of the final compounds **279** and **280** were isolated and although reaction times appear to be slightly longer than coupling to aromatic bromides this is an extremely useful and efficient coupling reaction which should find widespread use in liquid crystal chemistry. Compound **281** was similarly prepared in excellent yield.

The selectivity of alkynylzinc reagent coupling to bromo-iodo- substituted aromatic compounds was discussed earlier and the use of triflate derivatives now brings another variable into the selectivity discussion.

Compound **282** is a bromonaphthyl triflate which when coupled to the zinc derivative of compound **266** was expected to give compound **283** as the product; *i.e.* coupling was expected to take place at the triflate site (lithium chloride was added to the reaction mixture which was heated at ~67 °C). However, this reaction was carried out before it was found that aromatic bromides could be coupled to alkynylzinc reagents (see p 233). The reaction was carefully monitored by glc analysis which revealed the presence of only one monocoupled product (a small amount of starting material and the double coupled product were detected also) which was easily isolated by column chromatography. This compound (**283**) was prepared as an intermediate with the intention of further coupling at the bromo-site. However, compound **283** was found to be a strongly nematogenic material and the sample was recrystallised and kept as a final compound.

It seems quite strange that such a coupling should be quite so selective towards the triflate site. Especially when it is noted that when coupled in their own environments (see p 234) the couplings involving triflate derivatives appeared to be less reactive than those couplings involving aromatic bromo derivatives. It could perhaps be concluded that the triflate group deactivates the bromo site and/or the bromine activates the triflate site towards alkynylzinc coupling reactions. It could be that selectivity would be 100% towards the bromo site if lithium chloride was not added, however this would be impossible to determine as lithium chloride is produced in the reaction mixture during the formation of the zinc derivative from the lithium derivative with zinc chloride (lithium chloride is essential for the coupling involving aromatic triflate derivatives, see p 234).

Concurrently with this work, the selectivity of the iodotriflate derivative **285** towards coupling with alkynyl zinc reagents was investigated. Since it was already known that aromatic iodides coupled at room temperature and that aromatic triflate derivatives coupled at elevated temperatures[168] and required the presence of lithium chloride then total selectivity was anticipated. This was found to be the case; pent-1-ynylzinc chloride was coupled to compound **285** at room temperature in the absence of lithium chloride to give a good yield of compound **286**. Subsequent couplings with the zinc derivatives of compounds **263** and **266** at elevated temperature in the presence of lithium chloride gave excellent respective yields of the final compounds **287** and **288**.

Although the selectivity of the iodo-triflate derivative is more definite, the bromo-triflate derivative is equally attractive due to its easier preparation.

Summary of Experimental

The synthetic methods employed for this thesis represent a significant contribution to the synthesis of liquid crystal compounds. A wide cross-section of methods has been used including simple procedures, such as Friedel-Crafts acylations, Wolff-Kishner reductions and O-alkylations of phenols. The use of a diazotisation/replacement of anilines has provided vital intermediates. The DCC esterification technique proved to be very convenient which enabled the fast synthesis of large numbers of liquid crystalline esters.

The most important aspect of the synthetic procedures was the development of novel, selective palladium-catalysed cross-coupling reactions (see p 56). These reactions enabled the build up of both intermediates and final, liquid crystalline compounds of general substitution patterns. It seems almost certain that these convenient, high-yielding procedures will be developed further and feature strongly, not only in liquid crystal synthesis but also in general organic synthesis.

RESULTS AND CONCLUSIONS

3.1 Lateral Fluoro-substituted Esters[163]

Generally the ultimate aim in the synthesis of mesogenic materials is to obtain compounds which are low melting and have high liquid crystal phase thermal stabilities (*e.g.* low melting point and high $T_{N\text{-}I}$ value for display devices based on nematic materials).

However, this takes no account of the other vital physical parameters such as dielectric anisotropy, viscosity, birefringence, order parameters and elastic constants which are required to make the compounds suitable for use in a display device. It is, therefore, totally unrealistic to expect a single compound to have perfect characteristics for these display devices and several compounds need to be combined to give a mixture with an optimum range of properties. Often included in such mixtures are compounds which do not exhibit liquid crystal phases but have, for example, high positive values of dielectric anisotropy and/or low viscosities. Provided such additives are used in small amounts, they do not depress the $T_{N\text{-}I}$ value too much and most importantly they can reduce the threshold voltage of the device.

This is relevant to the aims of the lateral fluoro-substituted 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates (**44-57**). These compounds were intended to, hopefully, have low melting points but were never expected to have anything better than monotropic or virtual values of $T_{N\text{-}I}$ (*i.e.* low nematic tendency). Above all, the intention was to produce materials with very high values of positive dielectric anisotropy. It was hoped to do this by incorporating the lateral fluoro-substituents to break up the antiparallel correlations which exist in the parent (non-fluorinated) systems; such antiparallel associations give lower values of dielectric anisotropy than could be expected from the free molecules.[216-221] The fluoro-substituents will, of course, increase the positive dielectric anisotropy to some extent simply by the expected increase in the dipole moment.

Monofluoro-substituted esters ('Kelly esters') prepared by Schad and Kelly[180,217-221] (see compounds **291** and **292** in Table 3, p 240) were shown to have much higher values of positive dielectric anisotropy than their non-fluorinated analogues (much higher than could be accounted for by the additional dipole due to the fluoro-substituent). The Kirkwood correlation (*g*) factor is a quantitative expression of the extent of antiparallel correlation of a system. Essentially values less than 1 indicate a system with antiparallel associations and values greater than 1 reveal the presence of parallel associations; hence values of 1 are indicative of a system free of net associations.

Investigations into the *g* factors of these monofluoro-substituted (Kelly) esters by Schad and Kelly[218,219] showed a *g* factor of 1.0. However, subsequent investigations by our collaborators R.S.R.E. (Malvern)[220] have revealed (in certain homologues) values of *g* of greater than one which support the concept of parallel associations as suggested by Toriyama and Dunmur.[217] Such an occurrence is extremely important since, if structural reasons for an effect can be understood, then it may be possible to design molecular systems with greater parallel associations of molecular dipoles which would give much larger values of positive dielectric anisotropy, with the obvious advantage of low threshold voltages for applications in various electro-optic display devices. It was hoped that the preparation of a coherent set of multi-fluoro-substituted esters (compounds **44-57**) would help clarify the situation.

The lateral fluoro-substituted 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxybenzoates (**59-74**) were prepared to produce enantiotropic nematic materials of high positive dielectric anisotropy with the hope of much reduced melting points over the parent systems. Also this series serves to parallel the two-ring systems (compounds **44-57**) for comparison purposes but the series of larger molecules would of course have the disadvantages of higher viscosity and reduced solubility in nematic host materials.

As a compromise, the series of 4-cyanophenyl *trans*-4-propylcyclohexylethylbenzoates (**75** and **77**) were prepared in the expectation of enantiotropic T_{N-I} values whilst retaining the hoped for properties of the simple two ring systems (low melting points, better solubility in nematic host materials and, of course, very high values of dielectric anisotropy).

The esters (compounds **79-80**) shown in Scheme 9 (p 78) were prepared to see if they possessed more suitable properties for nematic display device purposes than their isomeric esters (compounds **291** and **44**). Compound **82** was prepared to investigate reports[222,223] that an ether unit in the alkyl chain of discotic systems (β-oxygen effect) increases the mesophase range by reducing the melting point and increasing the clearing point. Note: although the transition temperatures of compounds **79, 80** and **82** will be discussed, no other physical property results are available.

Substituted Benzoic acids

Four of the six acids used in the preparation of the esters shown in Table 3 and 4 are themselves liquid crystalline; transition temperatures (°C) for the parent 4-pentyl- and 4-butoxy- benzoic acids have been reported previously[224] as K 88.0 N 126.5 I and K 147.0 N 160.0 I respectively. The transition temperatures for the 2-fluoro-4-pentyl- and the 2-fluoro-4-butoxy- benzoic acids reported here are K 85.0 N 91.0 I and K 108.0 N 125.0 I respectively and the corresponding difluoro-substituted acids are not liquid crystalline (melting points of 78-79 and 113-114 °C respectively). The effect of monofluoro-substitution for these acids is similar to the effect for the esters themselves.

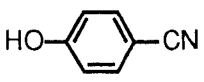
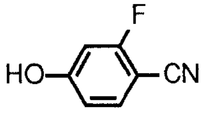
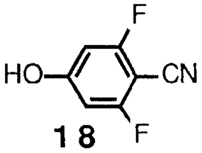
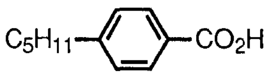
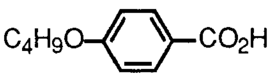
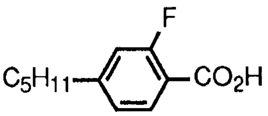
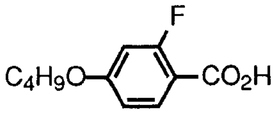
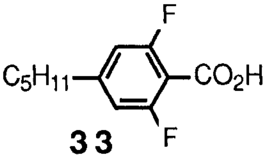
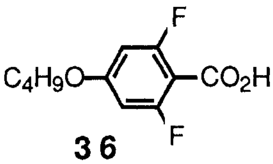
3.1 (a) Transition Temperatures (°C) for Fluoro-substituted 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates (compounds **44-57** and **289-292**, Table 3, p 240)

The transition temperatures recorded in Table 3 can be compared in many different ways to illustrate the trends caused by the various fluoro-substituents and the following discussion is an attempt to summarise these trends.

The melting points and the T_{N-I} values (enantiotropic, monotropic or virtual) of the 4-butoxy esters are always higher than those of the corresponding 4-pentyl esters by approximately 15 to 40 °C and 15 to 50 °C respectively. Such differences between alkyl and alkoxy compounds are typical of the differences seen in other systems. However, the butoxy esters all crystallise more readily than the corresponding pentyl esters and often this crystallisation occurs at a temperature above the N-I transition so that in many cases virtual values from mixtures in E7 (supplied by BDH Ltd.; see p 67) had to be obtained. Although the T_{N-I} values for the pentyl esters are lower than those for the butoxy homologues, monotropic T_{N-I} values were seen as low as -20.5 °C because the alkyl compounds had a reduced tendency to crystallise.

Table 3

Transition Temperatures (°C) for Fluoro-substituted 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates (**44-57** and **289-292**)

PHENOL / ACID	 **43**	 **25**	 **18**
 **42**	K-I = 64.5 N-I = (55.5) **289**	K-I = 30.5 N-I = (24.5) **291**	K-I = 29.5 N-I = (-8.0) **44**
 **20**	K-N = 92.0 N-I = 104.0 **290**	K-I = 72.0 N-I = (48.5) **292**	K-I = 71.5 N-I = [7.5] **45**
 **24**	K-I = 65.5 N-I = (32.0) **46**	K-I = 39.5 N-I = (-3.0) **48**	K-I = 55.0 N-I = (-20.5) **50**
 **27**	K-I = 90.0 N-I = (61.0) **47**	K-I = 55.0 N-I = (21.5) **49**	K-I = 68.5 N-I = [-6.0] **51**
 **33**	K-I = 74.5 N-I = [-18.0] **52**	K-I = 32.0 N-I = [-45.0] **54**	K-I = 36.5 N-I = [-67.0] **56**
 **36**	K-I = 101.0 N-I = [25.0] **53**	K-I = 56.0 N-I = (-1.5) **55**	K-I = 63.0 N-I = [-31.5] **57**

For a given 4-pentylbenzoate, one fluorine in the phenol ring (*ortho* to the nitrile group) has the effect of lowering the melting point by 34.0 °C for a non-fluoro-substituted benzoate (compounds **289** and **291**), by 26.0 °C for a monofluoro-substituted benzoate (compounds **46** and **48**) and by 42.5 °C for a difluoro-substituted benzoate (compounds

52 and **54**). A second fluoro-substituent *ortho* to the nitrile group causes only a further 1.0 °C fall in melting point for compound **44** but for the monofluoro- and difluoro-substituted benzoates (compounds **50** and **56**) the melting points are increased by 15.5 and 4.5 °C respectively. The trend for the corresponding 4-butoxybenzoates is similar; the decreases in melting point due to a fluoro-substituent in the phenol ring are 20.0, 35.0 and 45.0 °C for the non-fluoro-, monofluoro- and difluoro- benzoates respectively (compounds **290,292; 47,49; 53,55**). The second fluoro-substituent in the phenol ring causes a further lowering of the melting point for the non-fluorobenzoate of 0.5 °C (compound **45**) but for the monofluoro- and the difluoro- benzoates, increases in melting points of 13.5 and 7.0 °C respectively, are seen (compounds **51** and **57**).

Comparing the values in Table 3 to discern the effect of fluoro-substitution in the pentylbenzoate (acid) ring position of the molecule, we see that a fluoro-substituent in the acid ring increases the melting point by only 1.0 °C for the unsubstituted cyanophenyl ester (compounds **289** and **46**) and by 9.0 and 25.5 °C for the monofluoro- and the difluoro-cyanophenyl esters respectively (compounds **291,48; 44,50**). A second fluoro-substituent in the acid ring causes a further 9.0 °C increase in melting point for the unsubstituted cyanophenyl ester (compound **52**) whereas decreases in the melting point of 7.5 and 18.5 °C are seen for the monofluoro- and the difluoro- phenol rings respectively (compounds **54** and **56**). The trends for the corresponding butoxybenzoates are quite different however, and contrast with those discussed above. A monofluoro-substituent in the butoxybenzoate ring causes the melting point to fall by just 2.0 °C compared with an unsubstituted cyanophenyl ester (compounds **290** and **47**); this slight effect is similar to that seen for the pentyl esters, but for monofluoro- and difluoro- cyanophenyl esters the melting points are reduced by 17.0 and 3.0 °C respectively (compounds **292,49; 45,51**). Further fluoro-substitution in the acid ring now causes the melting points to rise by 11.0 and 1.0 °C for the unsubstituted and the monofluoro-substituted cyanophenyl esters respectively (compounds **53** and **55**) but for the difluorocyanophenyl ester a 5.5 °C fall in melting point is experienced (compound **57**).

The above discussion on melting points has considered the horizontal and vertical trends from Table 3, but a particularly striking observation emerges from the diagonal comparisons. A monofluoro-substituent in the acid ring (compound **46**) increases the melting point by 1.0 °C whereas a fluoro-substituent in the phenol ring (compound **291**) reduces the melting point by 34.0 °C. This trend repeats itself for the other comparison (compounds **52** and **44**) and similar trends are seen for the butoxy compounds. Overall melting points are reduced by fluoro-substitution (only compounds **52** and **53** have higher melting points than their parent systems) but a fluoro-substituent in the acid ring tends to increase melting points whereas a fluoro-substituent in the phenol ring reduces melting point.

Unlike the rather erratic trends in the melting points just discussed, the T_{N-I} values are always reduced by fluoro-substitution regardless of where the substituent is placed. However, the magnitude of the reduction does depend greatly on the position of the substituent.

For a given pentylbenzoate one fluorine in the phenol ring reduces the T_{N-I} value for an unsubstituted benzoate by 31.0 °C; and by 35.0 and 27.0 °C for the monofluoro- and difluoro- benzoates respectively (compounds **289,291; 46,48; 52,54**). Substituting a second fluorine in the phenol ring further reduces the T_{N-I} value by 32.5 °C in the case of an unsubstituted benzoate (compound **44**) (which is a similar effect to that caused by the first substitution), but when a monofluorobenzoate is considered the further fall in the T_{N-I} value is only 17.5 °C (which is approximately half of the first reduction, compound **50**). However, the further fall in the T_{N-I} value for the difluorobenzoate is 22.0 °C (compound **56**) and this is about the same as the original decrease caused by the first fluoro-substituent in the phenol ring.

The trends for the corresponding butoxybenzoates are fairly similar to those for the alkyl systems although reductions in the T_{N-I} values are much greater for unsubstituted or monofluoro-substituted acids and fairly similar when two fluoro-substituents are already present. For the butoxybenzoates, one fluoro-substituent in the phenol ring causes a big reduction in the T_{N-I} value of 55.5 °C (compounds **290** and **292**); for the mono- and di-fluoro benzoates the reductions are only 39.5 and 26.5 °C respectively (compounds **47,49**;

53,55). A second fluoro-substituent in the phenol ring causes a smaller decrease of 41.0 °C in the T_{N-I} value for the unsubstituted benzoate (compound **45**); the reduction is even less (27.5 °C) for the monofluorobenzoate (compound **51**) but increases to 30.0 °C for the difluorobenzoate (compound **57**); these trends are seen for the analogous pentyl compounds discussed above.

One fluoro-substituent in the pentylbenzoate ring for an unsubstituted phenol reduces the T_{N-I} value by 23.5 °C (compounds **289** and **46**), for a monofluoro-substituted phenol the reduction is a similar 27.5 °C (compounds **291** and **48**) but for a difluorophenol the reduction is only 12.5 °C (compounds **44** and **50**). A further fluoro-substituent in the benzoate ring causes a large fall in the T_{N-I} value of 50.0 °C for the unsubstituted phenol (compound **52**) and comparably large reductions of 42.0 and 46.5 °C for the mono- and di-fluoro- substituted phenols respectively (compounds **54** and **56**).

The trend for the corresponding butoxy esters is similar for the first fluoro-substituent in the acid ring (reductions in the T_{N-I} values of 43.0, 27.0 and 13.5 °C respectively: compounds **290,47**; **292,49**; **45,51**), but reductions caused by the second fluoro-substiuent (36.0, 23.0 and 25.0 °C respectively: compounds **53**, **55** and **57**) are much less than for the pentyl case discussed above.

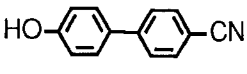
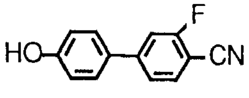
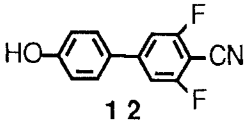
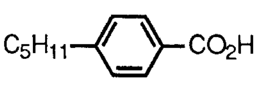
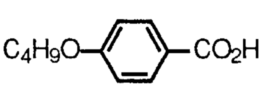
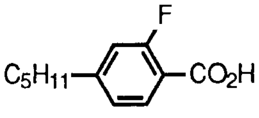
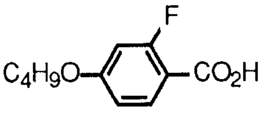
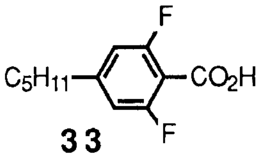
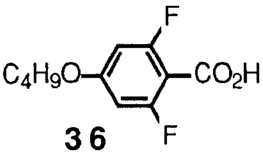
3.1 (b) Transition Temperatures (°C) for Fluoro-substituted 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxy- benzoates (compounds **59-74**, **293** and **294**, Table 4, p 244)

In the discussion of the phenyl esters it was noted that the melting points of the butoxy esters were always 15-40 °C higher than those of the corresponding pentyl esters (which is usual for such systems). It is therefore surprising to find that, for the series of biphenylyl esters, melting points are very similar and in a few cases the pentyl esters even have higher melting points than their butoxy analogues.

Enantiotropic nematic phases are seen for all of these esters and a fluoro-substituent reduces the T_{N-I} value by between 7 and 48 °C. The clearing points of the butoxy series are always higher than those for the corresponding pentyl esters, and the pentyl series of esters generally supercool further than do their butoxy analogues.

Table 4

Transition Temperatures (°C) for Fluoro-substituted 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxy- benzoates (**59-74**, **293** and **294**)

PHENOL ACID	 **58**	 **11**	 **12**
 **42**	K-N = 109.0 N-I = 237.5 **293**	K-N = 123.5 N-I = 198.5 **59**	K-N = 96.5 N-I = 150.5 **61**
 **20**	K-N = 120.0 N-I = 270.0 **294**	K-N = 135.0 N-I = 237.0 **60**	K-N = 114.5 N-I = 195.0 **62**
 **24**	K-N = 103.0 N-I = 225.0 **63**	K-N = 112.5 N-I = 187.5 **65**	K-N = 98.0 N-I = 143.5 **67**
 **27**	K-N = 94.0 N-I = 259.5 **64**	K-N = 115.0 N-I = 219.5 **66**	K-N = 104.0 N-I = 184.0 **68**
 **33**	K-N = 109.5 N-I = 191.0 **69**	K-N = 116.5 N-I = 158.0 **71**	K-N = 89.0 N-I = 121.0 **73**
 **36**	K-N = 94.0 N-I = 223.0 **70**	K-N = 103.0 N-I = 194.0 **72**	K-N = 102.0 N-I = 161.5 **74**

For a given pentylbenzoate, one fluoro-substituent in the biphenol ring (*ortho* to the nitrile group) raises the melting points by 14.5, 9.5 and 7.0 °C for the non-, mono- and di-fluoro-substituted benzoates respectively (compounds **293**,**59**; **63**,**65**; **69**,**71**). A second fluoro-substituent in the biphenol ring causes the melting points to decrease by 27.0, 14.5

and 27.5 °C respectively (compounds **61**, **67** and **73**) so that melting points are now even lower than the original values by 12.5, 5.0 and 20.5 °C respectively.

The trend for the corresponding butoxy esters is similar; monofluoro-substitution in the biphenol ring causes an elevation of the melting points for the non-, mono- and di-fluoro-substituted benzoates by 15.0, 21.0 and 9.0 °C respectively (compounds **294**,**60**; **64**,**66**; **70**,**72**). The second fluoro-substitution then causes respective falls in melting point of 20.5, 11.0 and 1.0 °C (compounds **62**, **68**, **74**) but the values for the latter two systems are still above the corresponding parent systems.

For a given biphenol, one fluorine in the pentyl benzoate ring leads to a lowering of the melting point of 6.0 and 11.0 °C for the non- and mono-fluoro-substituted esters respectively (compounds **293**,**63**; **59**,**65**) but for a difluoro-biphenyl ester (compounds **61** and **67**) the melting points increase slightly (1.5 °C). The second fluoro-substituent in the benzoate ring produces an interesting effect by increasing the melting points for the non- and mono- fluoro-substituted esters by 6.5 and 4.0 °C respectively (compounds **69** and **71**) but for the difluoro-substituted case a decrease of 9.0 °C occurs (compound **73**), *i.e.* the effect of the second fluoro-substituent in the acid ring approximately balances the effect caused by the first.

For the corresponding butoxy series the effect for the respective compounds as above is one of decreases in melting points of 26.0, 20.0 and 10.5 °C (compounds **294**,**64**; **60**,**66**; **62**,**68**) and for a second fluoro-substituent in the acid ring no change is recorded for the non-fluoro compound (**70**) whereas further falls in melting points of 12.0 and 2.0 are seen for the mono- and di- fluoro-substituted systems (compounds **72** and **74**). Just as for the phenyl esters discussed previously, these melting points are difficult to rationalise even though they do follow a general pattern.

However, the T_{N-I} values are much more predictable to the extent that fluoro-substitution always reduces the clearing point, but the degree of reduction (as for the phenyl esters) does depend greatly on the other substituents present. For a given pentylbenzoate, monofluoro-substitution in the biphenol ring reduces the clearing points (T_{N-I} values) by 39.0, 37.5 and 33.0 °C for the non-, mono- and di- fluoro-substituted benzoates respectively (compounds **293,59**; **63,65**; **69,71**). A second fluoro-substituent in the biphenol ring again causes a reduction in the clearing points by slightly greater values of 48.0, 44.0, 37.0 °C respectively (compounds **61**, **67** and **73**).

Both the trends and magnitude of the reductions are very similar for the butoxy equivalents, these being 33.0, 40.0 and 29.0 °C (compounds **294,60**; **64,66**; **70,72**) and 42.0, 35.5 and 32.5 °C (compounds **62**, **68** and **74**) in the same order as the above comparisons.

For a given biphenol, one fluoro-substituent in the pentylbenzoate ring reduces the $T_{N\text{-}I}$ values of the non-, mono- and di- fluoro-substituted esters by 12.5, 11.0 and 7.0 °C respectively (compounds **293,63**; **59,65**; **61,67**). These reductions are obviously much smaller than the reductions seen above for fluoro-substitution *ortho* to the nitrile group. However, a second fluoro-substituent in the benzoate ring brings increased and more typical reductions in the $T_{N\text{-}I}$ values of 34.0, 29.5 and 22.5 °C respectively (compounds **69**, **71**, **73**). This interesting trend is repeated for the corresponding butoxy esters. The decreases in $T_{N\text{-}I}$ due to the first fluorine in the acid ring are 10.5, 17.5 and 11.0 °C (compounds **294,64**; **60,66**; **62,68**) and the larger, more typical reductions caused by a second fluoro-substituent in the acid ring are 36.5, 25.5 and 22.5 °C (compounds **70**, **72** and **74**) for the non-, mono- and di- fluorobiphenols respectively.

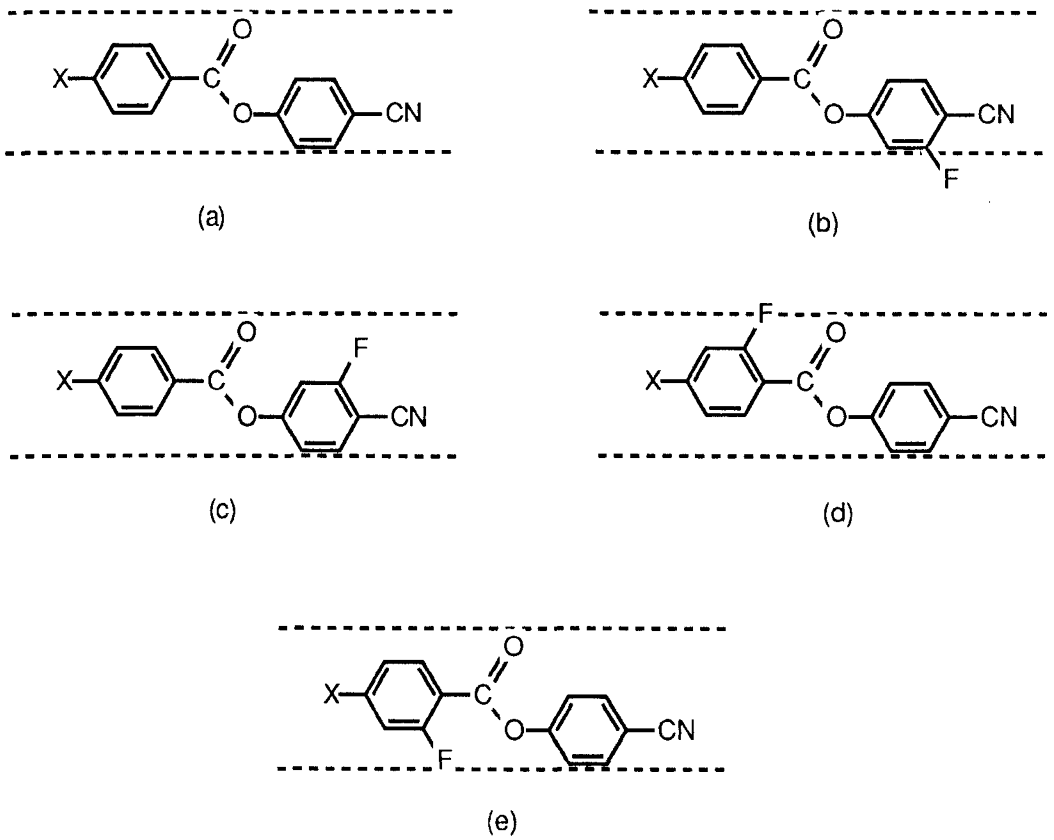
Summary of Sub-sections 3.1 (a) and 3.1 (b)

The discussion of the effect of fluoro-substitution on the $T_{N\text{-}I}$ values for both the phenyl- and the biphenylyl- benzoates are summarised by three distinct substitution effects.

Firstly, monofluoro-substitution in the phenol ring (*i.e.* *ortho* to the nitrile group) has a greater effect on the $T_{N\text{-}I}$ values of esters than monofluoro-substitution in the acid ring [*e.g.* compare compounds **289/291** (31.0 °C difference) and compounds **289/46** (23.5 °C difference); compounds **290/292** (55.5 °C difference) and compounds **290/47** (43.0 °C difference): the equivalent comparison for the biphenylyl esters shows compounds **293/59** (39.0 °C difference) and compounds **293/63** (12.5 °C difference); compounds **294/60** (33.0 °C difference) and compounds **294/64** (10.5 °C difference)].

Secondly, a second fluoro-substituent in the phenol causes a further depression in the T_{N-I} value which is approximately equivalent to that of the first fluoro-substitution *i.e.* the effects are approximately additive [*e.g.* compare compounds **289**, **291**, **44** (31.0 and 32.5 °C decrease); compounds **290**, **292**, **45** (55.5 and 41.0 °C decrease): the equivalent comparisons for the biphenylbenzoates are compounds **293**, **59**, **61** (39.0 and 48.0 °C decrease); compounds **294**, **60**, **62** (33.0 and 42.0 °C decrease)].

Thirdly, a second fluoro-substituent in the acid ring causes a larger depression in the T_{N-I} value than that caused by a single fluoro-substituent in the acid ring [*e.g.* compare compounds **46** and **52** (50.0 °C difference) and compounds **289** and **46** (23.5 °C difference); compounds **48** and **54** (42.0 °C difference) and compounds **291** and **48** (27.5 °C difference): the equivalent comparisons for the biphenylyl esters are compounds **63** and **69** (34.0 °C difference) and compounds **293** and **63** (12.5 °C difference); compounds **65** and **71** (29.5 °C difference) and compounds **59** and **65** (11.0 °C difference)].



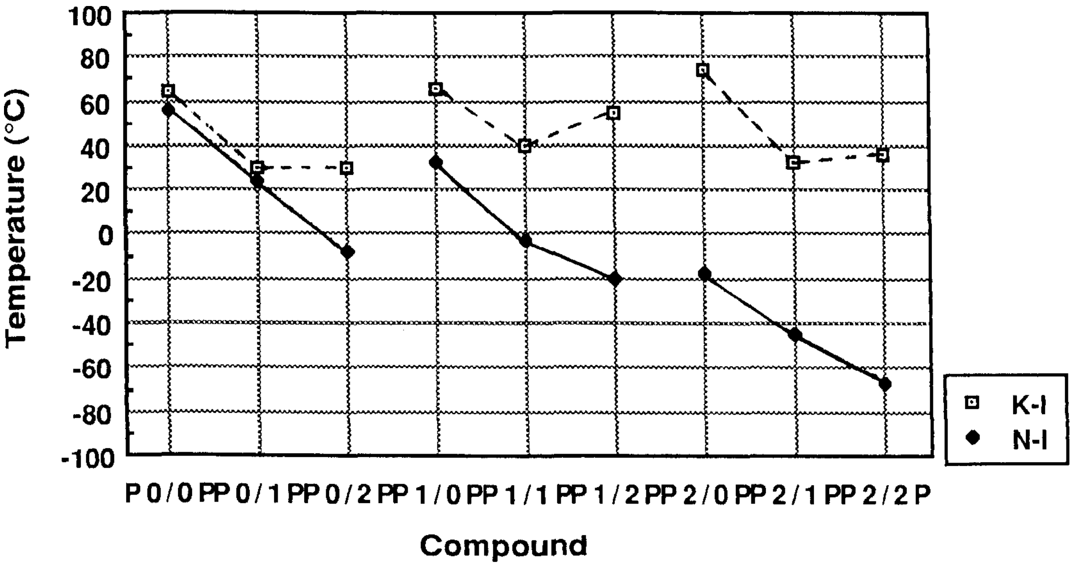
(a) (b) (c) (d) (e)

Conformations of Some Fluoro-substituted phenyl benzoates

Figure 35

These three distinct effects can be explained by considering how fluoro-substitution affects the breadth of the molecule. In Figure 35 (a), the natural breadth of the parent (unfluorinated) molecule is shown by the dotted line. Monofluoro-substitution in the phenol can give one extreme planar conformation (b) in which the substituent increases the breadth of the molecule. There is no particular reason why this conformation or the extreme alternative (c) produced by the rotation about the O-aryl bond would be preferred and therefore half the molecules will have a breadth equal to the parent system. With a second fluorine in the phenol ring it is inevitable that all molecules will be appreciably broader than the parent system (a) and these effects will be additive. For fluoro-substitution in the acid ring of the ester, the fluoro-substituent placed as shown in (d) may suffer electro-static repulsion by the carbonyl oxygen atom and the alternative conformation (e), which does not cause any broadening of the molecule, would be preferred. The first fluoro-substituent in the acid ring should therefore have a small effect on the T_{N-I} value but a second fluoro-substituent would inevitably cause broadening of the molecules leading to much larger reduction in the T_{N-I} value.

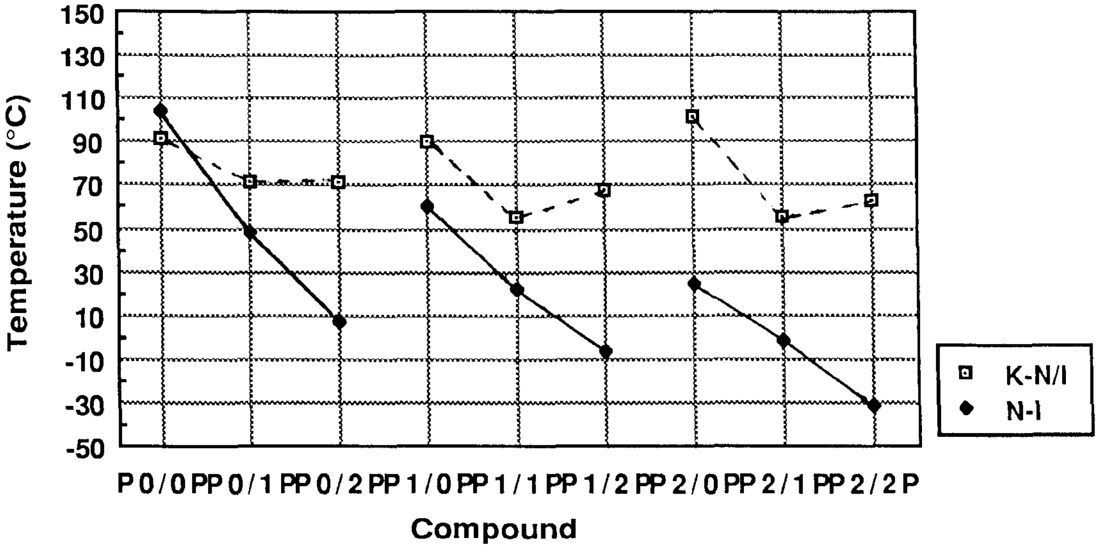
All these effects of fluoro-substitution can be seen at glance by reference to Figures 36-39 which reveal the trends much more clearly than the figures in Tables 3 and 4.



Transition Temperatures (°C) for Fluoro-substituted alkylphenyl benzoates

Figure 36

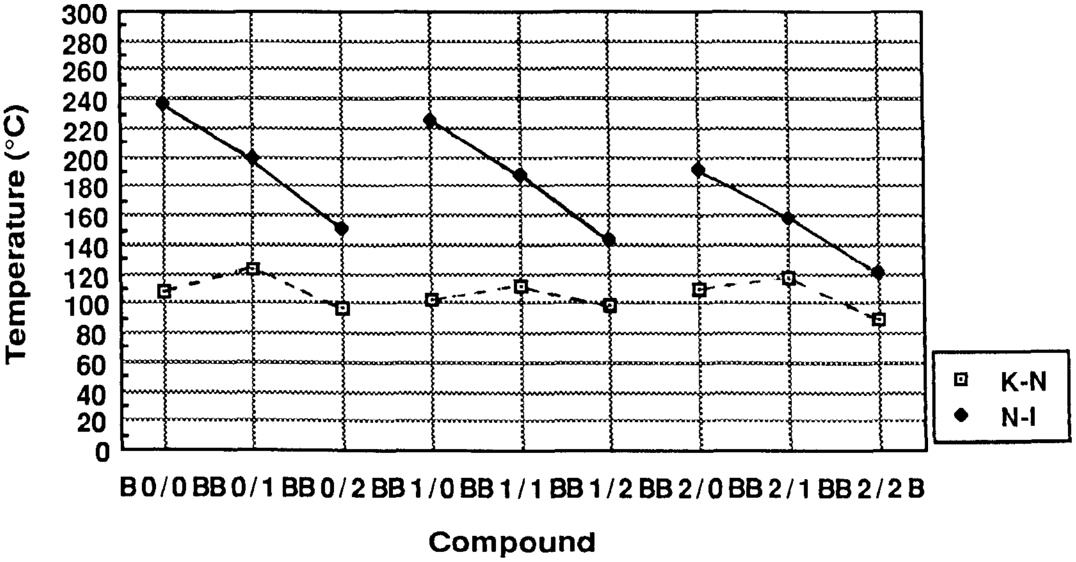
The four figures each show the title esters in three separate groups where x/y on the abscissa refers to x fluoro-substituents in the acid ring and y fluoro-substituents in the phenol ring (*e.g.* in Figure 36, 2/1 signifies compound **54**).



Transition Temperatures (°C) for Fluoro-substituted alkoxyphenyl benzoates

Figure 37

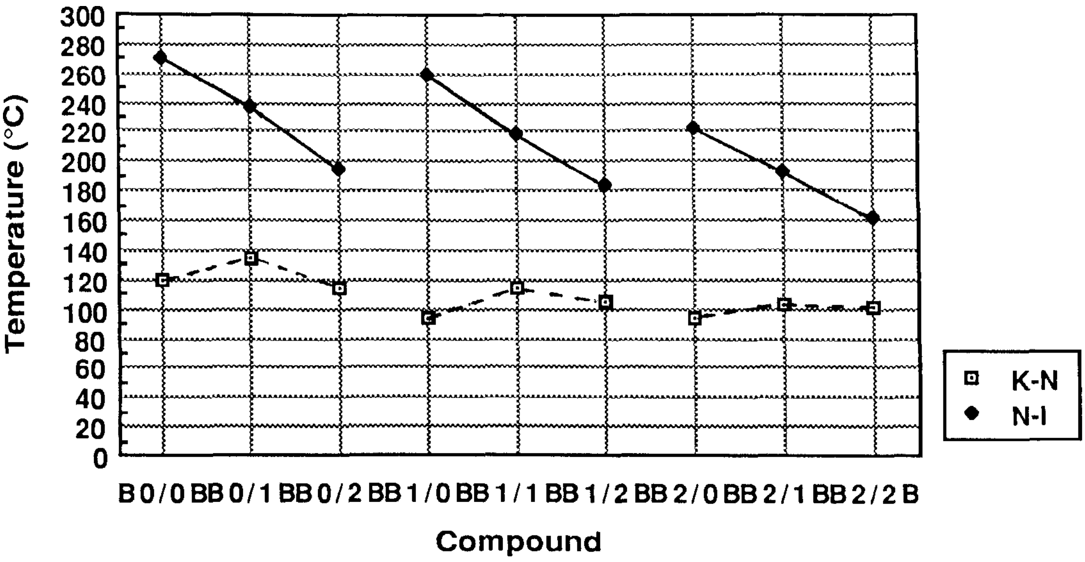
Figures 38 and 39 with enantiotropic T_{N-I} values more clearly (and reliably) show the following points: (a) a narrow spread of melting points, showing a rise and then a fall



Transition Temperatures (°C) for Fluoro-substituted alkylbiphenyl benzoates

Figure 38

with mono- and di- fluoro- substitution respectively in the phenol (dashed line); (b) the approximately additive effect in the depression of the T_{N-I} values caused by mono- and di-fluoro-substitution in the phenol ring (the almost linear arrangement of the three points connected by full lines); (c) the smaller, then larger effect on the T_{N-I} values caused by the fluoro-substitutions in the acid ring (one example is shown in each figure as a dotted line).



Transition temperatures (°C) for Fluoro-substituted alkoxybiphenyl benzoates

Figure 39

Very similar results are revealed in Figures 36 and 37 for the phenyl bezoates but here monotropic (and less certain virtual) values are being considered. The pattern of melting points, however, shows a fall then a rise for fluoro-substitution in the phenol ring [which is unlike the rise then a fall trend described in (a) above].

In conclusion, from a transition temperature point of view, fluoro-substitution in the two-ring phenyl benzoates renders such systems completely unattractive because of the large reductions in already low T_{N-I} values accompanied by never very great decreases in melting points. Fluoro-substitution in the three-ring biphenylyl benzoates has been of great benefit in certain (two fluorines in the biphenol ring) cases giving lower melting compounds which still have high T_{N-I} values, however in many cases the melting points have actually increased. Fortunately, transition temperatures are just one consideration of the suitability of a compound for use in nematic mixtures for say a twisted nematic display device.

3.1 (c) Transition Temperatures (°C) for Fluoro-substituted 4-cyanophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoates (compounds **75-77**, Table 5, p 251)

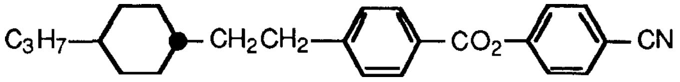
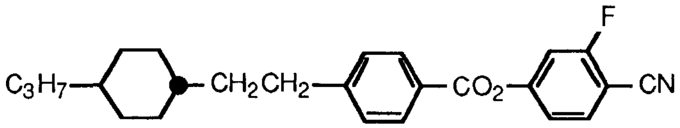
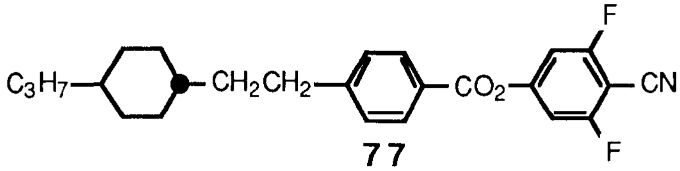
More interest has been shown in compounds with fluoro-substituents *ortho* to the nitrile group, so only this type of compound has been prepared for the ethyl-linked cyclohexyl-substituted systems.

These compounds can be directly compared with the analogous phenyl benzoates (compounds **289**, **291** and **44** respectively) and biphenylyl benzoates (compounds **293**, **59** and **61** respectively).

Table 5

Transition Temperatures (°C) for Fluoro-substituted 4-cyanophenyl

4-(*trans*-4-propylcyclohexylethyl)benzoates (**75-77**)

Compound	Transition Temperatures (°C)
 **75**	K 90.0 N 194.0 I
 **76**	K 59.0 N 167.0 I
 **77**	K 55.0 N 134.5 I

The melting point trend is very similar to that for the phenyl benzoates; *i.e.* large decrease (31.0 °C) on the first fluorination [compare compounds **75** and compound **76**] then a much smaller decrease (4.0 °C) due to the second fluoro-substituent (compound **77**). This trend is not surprising since these compounds are closely related to the phenyl benzoates considered previously. The values of the melting points are around 30 °C higher than those for the phenyl benzoates (compounds **289**, **291** and **44**) but are 19.0 °C (parent system), 64.5 °C (monofluoro system) and 41.5 °C (difluoro system) lower than for the biphenylyl benzoates (compounds **293**, **59** and **61**).

The T_{N-I} values for compounds **75-77** (194.0, 167.0 and 134.5 °C respectively) are all enantiotropic and are much higher (~140 °C) than those for the phenyl benzoates (compounds **289**, **291** and **44**; monotropic T_{N-I} values of 55.5, 24.5 and -8.0 °C respectively). In fact, their T_{N-I} values are only slightly less (43.5, 31.5 and 16.0 °C for the non-, mono-, and di- fluoro-substituted systems respectively) than those for the biphenylyl benzoates (compounds **293**, **59** and **61**, T_{N-I} values of 237.5, 198.5 and 150.5 °C respectively).

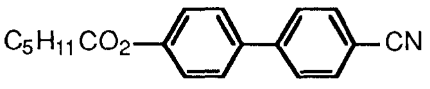
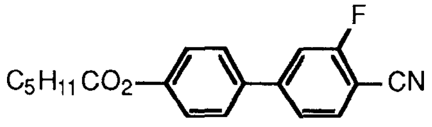
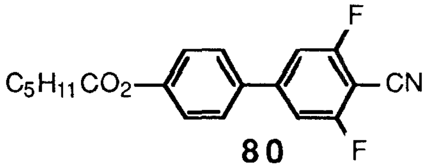
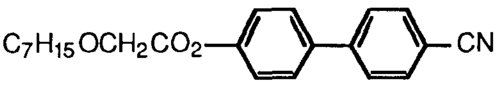
The reasonably low melting points and very high T_{N-I} values are exactly what it was hoped these compounds would show *i.e.*, they combine the low melting points of the phenyl benzoates with the high T_{N-I} values of the biphenylyl benzoates. Therefore, from a transition temperature point of view, these compounds (especially the mono- and di-fluoro-substituted systems) could be very useful as major components in nematic mixtures for twisted nematic and supertwisted nematic display devices.

3.1 (d) Transition Temperatures (°C) for Fluoro-substituted 4-cyanobiphenyl-4'-yl hexanoates and 4-Cyanobiphenyl-4'-yl heptoxyethanoate (compounds **295**,[36] **79**, **80** and **82**, Table 6, p 253)

The first three compounds in Table 6 are isomeric with the phenyl benzoates **289**, **291** and **44** respectively but the trends in both melting point and T_{N-I} values are quite different. The melting point of the parent system (compound **295**, mp 53.0 °C) is lower than that of the parent phenyl benzoate (compound **289**, mp 64.5 °C) by 11.5 °C. The monofluoro-substituted analogue (compound **79**, mp 35.5 °C) has a reduced melting point (by 17.5 °C) due to the first fluoro-substituent which is approximately half the corresponding reduction seen in the phenyl benzoates; a second fluoro-substituent (compound **80**, mp 58.0 °C) causes a large increase in melting point to give a greater value than the parent system (the second fluoro-substituent in the phenyl benzoates had virtually no effect on the melting point).

Table 6

Transition Temperatures (°C) for Fluoro-substituted 4-cyanobiphenyl-4'-yl hexanoates (**295**,[36] **79** and **80**) and 4-Cyanobiphenyl-4'-yl heptoxyethanoate (**82**)

Compound	Transition Temperatures (°C)
 **295**	K 53.0 N 70.5 I
 **79**	K 35.5 (N 25.0) I
 **80**	K 58.0 [N -13.0] I
 **82**	K 51.5 (S_A 40.5 N 41.5) I

The T_{N-I} values are always reduced on fluoro-substitution (as they are in the phenyl benzoates) and the enantiotropic value of the parent compound **295** (70.5 °C) is higher than that for its isomeric phenyl benzoate (**289**; monotropic T_{N-I} value 55.5 °C). However, the T_{N-I} values for the monofluoro-substituted compounds **79** and **291**) are almost the same (25.0 °C) and the difluoro-substituted compound **80** has a virtual T_{N-I} value (-13.0 °C) which is lower than that for the equivalent phenyl benzoate (compound **44**, T_{N-I} value -8.0 °C).

It appears that the biphenylyl hexanoates are inherently more nematic in character and of lower melting point (see **295** and **289**) but fluoro-substitution causes a larger reduction in the T_{N-I} value and gives greater melting points (compare compounds **79** and **80** with compounds **291** and **44** respectively). These trends render the hexanoates even more unsuitable for use in display devices than the phenyl benzoate systems.

For compound **82**, the possibility of a reduced melting point with an increased T_{N-I}

value in comparison with compound **295** was not realised; the T_{N-I} value is much reduced and the melting point is little changed and an S_A phase has been induced.

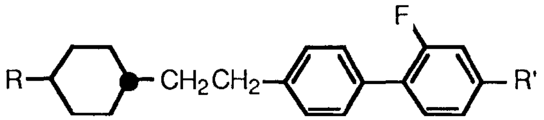
No results on the physical properties of any of these compounds (**295**, **79**, **80** and **82**) are available yet.

3.1 (e) Physical Properties of Fluoro-substituted 4-cyanophenyl 4-pentyl- and 4-butoxy- benzoates (compounds **44-57** and **289-292**, Table 7, p 257)

Publications relevant to this discussion[216-221] and our collaborators at R.S.R.E. (Malvern) are primarily concerned with alkyl-substituted systems because of their lower viscosity and greater solubility in host materials. For this reason, the results for the 4-pentyl-substituted series are mainly discussed here and those for the 4-butoxy-substituted analogues are commented on briefly.

As mentioned in the introduction to this section (p 237) there have been several papers in this area of work, which is still of considerable interest. It is, therefore, surprising to note the contradictory nature of these publications. Most of the work in this area is by Schad and Kelly (see their brief letter[218] and full paper[219]) whose 4-cyano-3-fluorophenyl 4-alkylbenzoates have dielectric anisotropies ($\Delta\varepsilon$) much higher than the parent systems. The heptyl homologue has a small enantiotropic nematic range (K 28.0 N 28.5 I) and is therefore the best compound to use since measurements can be carried out on the single component or mixtures in a nematic phase. A dielectric anisotropy value of 48.9 was reported[218,219] which was measured on the neat compound just below the T_{N-I} value (not an extrapolated value from say a 10% mixture in I compounds; see later). Schad and Kelly measured the *g* factor (see previously p 237) as 1.0, and so they ascribed the high value of $\Delta\varepsilon$ to the combination of a higher dipole moment (6.1 compared to the parent systems 5.6) and the total break-up of antiparallel correlations as compared to the parent system ($\Delta\varepsilon$ of 19.9, measured on the neat material) which has a *g* factor of 0.7. Toriyama and Dunmur[217] however were the first to propose the possibility of parallel associations in such monofluoro-substituted systems and our collaborators at R.S.R.E. (Malvern)[220] have also recorded *g* factor values of greater than 1 adding support to this suggestion. Certainly Raynes, McDonnell and Smith [R.S.R.E. (Malvern)]^{220} believe that high values of Δε for the 'Kelly esters', especially those with short alkyl chains (C_2H_5- and C_3H_7-) are due not solely to the break-up of the antiparallel associations and to the extra dipole from the fluoro-substituent but also to the formation of parallel associations (evidence provided by *g* factor values greater than 1).

All the values of Δε for the compounds shown in Table 7 were measured as extrapolated values from 10 wt% solutions in a ternary mixture of I compounds.



R=3, R'=2 (I 32) : R=3, R'=5 (I 35) : R=5, R'=2 (I 52) (1:1:1)

By comparing compounds **289** and **291** with their heptyl homologues (see above) it can be seen what a vast difference the method of measurement can have on the Δε values. Dipole moments are slightly lower for both the heptyl compounds and the Δε value of 40.1 for compound **289** is much higher than that for the heptyl homologue (19.9, neat material) and in the 'Kelly ester' case the value of 41.0 for compound **291** is slightly lower than its heptyl homologue (48.9, neat material). The reason, of course, is that the host material (I compounds), from which Δε measurements for compounds **289** and **291** are derived, breaks up inter-molecular associations be they antiparallel or parallel in type. In the highly antiparallel correlated parent system true values of ~20 are measured from the neat compound but in the I compound host the break-up of these antiparallel associations leads to values of ~40. In the Kelly system, which as a pure compound has no net antiparallel correlations to break up (*g* factor of 1.0; see previously), the values should be similar. In fact, a slightly lower value is produced from the I compounds which perhaps suggests that parallel associations which exist in the neat Kelly systems [reported by Toriyama and Dunmur^{217} and by R.S.R.E. (Malvern)^{220}] are being broken down (thus giving a reduced Δε value).

From a practical point of view, since the ultimate destination of such high Δε additives would be in nematic host mixtures (*e.g.* I compounds), the Δε values of the pure compounds seem of academic interest. If antiparallel correlations of such parent systems and any parallel associations of the Kelly esters are broken up in the mixtures in which they are intended to be used, then it seems best to carry out measurements in a wide range of environments.

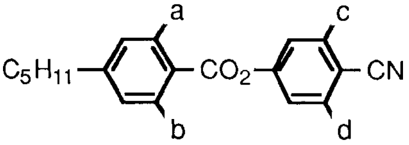
The compounds prepared for this section (**44-57**) have quite low nematic thermal stabilities (see p 240) in that all $T_{N\text{-}I}$ values are either monotropic or virtual (extrapolated from up to 30 wt% mixtures in E7), and so measurements of Δε were made from 10 wt% mixtures in the I compounds (see p 255). This rules out any discussion of *g* factors, since on the basis of the arguments above, no associations will remain in such an environment. Therefore the values of dielectric anisotropy (Δε) for the esters reported here should reflect the very high dipole moment values, and this is generally the case. It is impossible to provide comparisons in every way for this comprehensive set of esters (compounds **289-292** and **44-57**), but there are many interesting points to mention and some notable exceptions to the general trends.

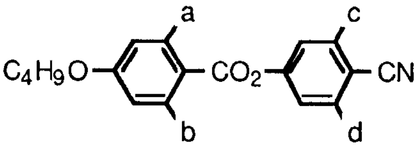
Firstly consider the series of compounds **289**, **291** and **44**; the dipole moment values (5.9, 6.6 and 7.2 respectively) rise as expected with increasing number of fluoro-substituents *ortho* to the cyano group. The increase in dielectric anisotropy value (in the I compound host) due to the first fluorine (compound **291**) is negligible (0.9), but the second fluoro-substituent of compound **44** causes the dielectric anisotropy value to increase dramatically by 20.0.

Compound **46** with one fluorine *ortho* to the ester linkage has a slightly lower dielectric anisotropy value (38.6) than its isomer (compound **291**) which could be explained simply in terms of the lower dipole moment value. Compound **52**, however, has an even lower dielectric anisotropy value 36.3 despite having a higher dipole moment value. The situation improves if a further fluorine is substituted *ortho* to the nitrile group (compound **54**) but the dielectric anisotropy value of 40.0 is still far short of that expected based on the dipole moment value of 7.4. This result is strikingly incompatible with the result for the isomeric compound (**50**) which has only a marginally higher dipole moment

Table 7

Some Physical Property Results for Fluoro-substituted 4-cyanophenyl 4-butoxy- and 4-pentyl- benzoates **(44-57, 289-292)**



Compound					Physical Property Results				
No.	a	b	c	d	Viscosity (cP)	Dipole (D)	$\varepsilon_{\parallel}$	$\varepsilon_{\perp}$	$\Delta\varepsilon$
289	H	H	H	H	47	5.9	49.9	9.8	40.1
291	H	H	F	H	33	6.6	51.3	10.3	41.0
44	H	H	F	F	-	7.2	70.7	9.7	61.0
46	F	H	H	H	-	6.4	47.2	8.6	38.6
48	F	H	F	H	-	7.1	61.0	10.4	50.6
50	F	H	F	F	-	7.7	74.9	10.0	64.9
52	F	F	H	H	30	6.8	44.2	7.9	36.3
54	F	F	F	H	86	7.4	59.0	19.0	40.0
56	F	F	F	F	-	8.0	71.1	11.8	59.3
									
290	H	H	H	H	-	-	-	-	-
292	H	H	F	H	-	7.1	58.0	8.3	49.7
45	H	H	F	F	-	7.8	77.0	10.2	66.8
47	F	H	H	H	-	6.9	50.1	7.5	42.6
49	F	H	F	H	-	7.5	64.5	10.7	53.8
51	F	H	F	F	-	8.0	80.8	11.3	69.5
53	F	F	H	H	-	-	52.1	7.6	44.5
55	F	F	F	H	-	7.9	64.1	9.9	54.2
57	F	F	F	F	-	8.3	69.2	10.7	58.5

value (by 0.3) yet has a dielectric anisotropy value of 64.9! In fact even compound **48**, with a lower dipole moment value than compound **54**, and only two fluoro-substituents has a much higher dielectric anisotropy value (50.6 *vs.* 40.0). The extra fluoro-substituent *ortho* to the ester linkage in going from compound **50** to compound **56** increases the dipole moment value slightly (by 0.3) but has reduced the dielectric anisotropy value (by 5.6). The equivalent comparison of the extra fluoro-substituent being *ortho* to the nitrile group shows the effect of dramatically increasing the dielectric anisotropy value by 19.3 (compounds **54** and **56**). It appears that those compounds with more fluorine substituents in the acid ring than in the phenol ring (*i.e.*, compounds **46**, **52** and **54**) have particularly low $\Delta\varepsilon$ values (38.6, 36.3 and 40.0 respectively) which are lower than the dipole moment suggests (all slightly lower than the 40.1 of the parent system, **289**). This is emphasised by the fact that compounds **44** and **50** have larger $\Delta\varepsilon$ values (61.0 and 64.9 respectively) than the 59.3 recorded for the tetrafluoro system (**56**); respective dipole moments are 7.2, 7.7 and 8.0. It is possible that values of $\Delta\varepsilon$ are being affected by interaction of the fluorine atoms in the acid ring with the ester group; this type of intra-molecular force would perhaps not affect the dipole moment values and would not be affected by a host material. The results clearly indicate that fluoro-substituents *ortho* to the nitrile group have the effect of increasing the dielectric anisotropy values much more than fluoro-substituents *ortho* to the ester linkage (which in some cases actually reduce the values) and yet the dipole moment values are similar in each case.

These observations are in agreement with similar trends in dipole moment values and dielectric anisotropy values for the equivalent butoxy-substituted series of esters and the same structural explanation may be advanced.

A few viscosity measurements are reported in Table 7 and higher values are expected for the butoxy homologues.

<u>Conclusion of Sub-section</u> 3.1 (e)

In general, bearing in mind the mode of measurement, the greater the number of fluoro-substituents the greater the dipole moment and the greater the dielectric anisotropy ($\Delta\varepsilon$); exceptions to this generalisation have been discussed above. Clearly the compounds with two fluoro-sustituents *ortho* to the nitrile group look most interesting, especially compound **44** and its butoxy analogue (**45**) which have dielectric anisotropy values of 61.0 and 66.8 respectively. Similar compounds to these, but with an additional fluoro-substituent *ortho* to the ester linkage (compounds **50** and **51**), have even greater dielectric anisotropy values (64.9 and 69.5 respectively), but their higher melting points and lower nematic phase thermal stabilities, combined with the expected lower solubility in host materials make these compounds (**50** and **51**) less attractive.

In work carried out by Dr D. Coates (BDH Ltd.), compounds **45** and **51** have recently been used as dopants (5 wt%) in a BDH commercial mixture (16817) with the desired effect of reducing the threshold voltage without depressing the T_{N-I} value too much. Of the two compounds, it is compound **45** which seems to be more suitable because it lowers the T_{N-I} value less and is more soluble in host materials. These promising preliminary results mean that tests will continue.

The trends are identical for the pentyl and the butoxy systems. The mode of measurement greatly affects $\Delta\varepsilon$ values of compounds whose molecules in their pure state are associated in some way.

The objective of high $\Delta\varepsilon$ values was achieved but, the poor solubility in host materials, high viscosities and low nematic thermal stabilities, militate against this type of compound being used in nematic mixtures for display device purposes. However, the most recent results given above do indicate that one or two of these compounds might, in small percentages, be of some use.

3.1 (f) Physical Properties of Fluoro-substituted 4-cyanobiphenyl-4'-yl 4-pentyl- and 4-butoxy- benzoates (compounds **59-74**)

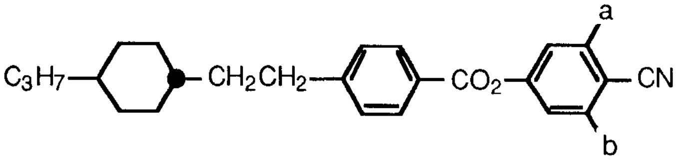
Our collaborators at R.S.R.E. (Malvern) had several problems with the low solubility of these compounds in any available host material and they have reported on just one compound (**61**) which has an extremely high viscosity (420 cP) and slightly lower dipole moment (7.5) and $\Delta\varepsilon$ value (54.0) than the two ring system (compound **44**). The general feeling is that although these systems have very high T_{N-I} values their low solubility in host materials and their very high viscosities make them even less suitable than the phenyl benzoate systems for display device nematic mixtures.

3.1 (g) Physical Properties of Fluoro-substituted 4-cyanophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoates (compounds **75-77**, Table 8, p 260)

As was hoped (and discussed on p 251), the melting points of these compounds are quite low and the $T_{N\text{-}I}$ values are high. On this basis alone the compounds appear better suited for nematic mixtures for display devices than both those types already discussed (p 254).

Table 8

Some Physical Property Results for Fluoro-substituted 4-cyanophenyl 4-(*trans*-4-propylcyclohexylethyl)benzoates **(75-77)**



Compound No.	a	b	Dipole (D)	$\varepsilon_{\parallel}$	$\varepsilon_{\perp}$	$\Delta\varepsilon$ (neat material)
75	H	H	6.0	33.0	5.5	27.5 (-----)
76	F	H	6.8	42.0	5.8	36.2 (37.0)
77	F	F	7.5	58.0	5.9	52.1 (66.0)

The dipole moment and dielectric anisotropy ($\Delta\varepsilon$) values are shown in Table 8 and as for other compounds discussed previously, the $\Delta\varepsilon$ values were obtained from extrapolation from 10 wt% solutions in a ternary mixture of I compounds (see p 255). However, $\Delta\varepsilon$ values for compounds **76** and **77** could also be obtained for the neat materials at 60 °C and these results are shown in parenthesis in the table.

The value (37.0) for the neat material for the monofluoro compound (**76**) is only very slightly greater than the extrapolated value from the I compound host (36.2); both these values are lower than for the analogous phenyl benzoate system (48.9 and 41.0

respectively for compound **291**). This suggests that neat compound **76** is very nearly free of all associations. The difluoro-substituted compound (**77**), however, reveals a significantly higher $\Delta\varepsilon$ value (66.0) in the neat state for this class of system than from measurements in the I compound host (52.1). This suggests the presence of parallel associations in the neat material (responsible for the high $\Delta\varepsilon$ value) which are destroyed in the I compound host (giving rise to a reduced $\Delta\varepsilon$ value). The value of 52.1 in the absence of parallel associations is still very high compared to the values of several multi-fluoro-substituted phenyl benzoate systems (see Table 7, p 257).

Conclusion of Sub-section 3.1 (g)

The cyclohexyl compounds (**75-77**) have high $\Delta\varepsilon$ values similar to their phenyl benzoate analogues; however, due to these compounds having much higher $T_{N\text{-}I}$ values, they should be far more suitable for display device purposes (as dopants present in high percentage). This comment applies particularly to compound **77** with its high positive value of $\Delta\varepsilon$ and the added advantage of low melting point and high $T_{N\text{-}I}$ value. However, our collaborators at R.S.R.E. (Malvern) have reported that $\varepsilon_{||}$ relaxes too much at low frequencies for both compounds **76** and **77** (a problem sometimes associated with three-ring systems) and this makes them unsuitable for use in single frequency high-level multiplexing mixtures; also, the cross-over frequency is not quite low enough for use in two-frequency applications.

3.2 Lateral Substituted Terphenyls and Related Systems

Much interest surrounds monofluoro-substituted terphenyls, with fluorine in the centre ring, as prepared by Chan.[127-130] The original intention of this work was to produce materials with high T_{N-I} values for use as nematic host materials. However, the work revealed additionally that such systems can produce tilted smectic mesophases (*e.g.* S_C, S_I) and so the compounds found use as host materials for ferroelectric (S_C*) mixtures which are used in ferroelectric display devices.

Ideal host materials for ferroelectric (S_C*) mixtures would be low melting, have the phase sequence K-S_C-S_A-N-I, with large S_C ranges and small S_A and N ranges [the short range S_A and N phases are required to give good alignment (see Introduction, p 45)] with no smectic phase below the S_C phase. They should have negative dielectric anisotropy ($-\Delta\varepsilon$), low viscosities and be of low birefringence. The monofluoro-substituted terphenyls (see above) have the disadvantage of slight positive dielectric anisotropy ($+\Delta\varepsilon$) and often have smectic phases below the S_C phase.

This section of work concerns the synthesis of compounds which are more suited for use as host materials in ferroelectric (S_C*) mixtures, primarily for display device purposes.

The work discussed here consists of five distinct sub-sections:

(a) two unfluorinated (parent) terphenyl systems to complete comparisons of transition temperatures, and several monofluoro-substituted terphenyls with a fluoro-substituent in every possible position of an end-ring;

(b) several difluoro-substituted terphenyls where the two fluorines are not *ortho* to each other;

(c) the largest sub-section, covering *ortho*-difluoro-substituted systems (in addition to the many terphenyl compounds synthesised a few analogous biphenyl systems have been prepared and to show the effect of multi-fluoro-substitution, a trifluoro- and a tetrafluoro- substituted terphenyl have also been made);

(d) terphenyl systems analogous to those above with a lateral nitrile substituent;

(e) one example of a terphenyl with a lateral trifluoromethyl-substituent.

3.2 (a) Lateral Monofluoro-substituted Terphenyls and Some Parent Systems

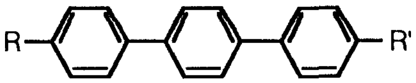
The two parent systems (compounds **97** and **98**) were prepared so that their transition temperatures could be compared with those of the analogous fluoro-substituted systems.

The monofluoro-substituted terphenyls (schemes 11 and 12, p 80 and 81) were nearly all prepared after the synthesis of the *ortho*-difluoro-substituted terphenyls (schemes 16-20, p 85-89) in order to have a full set of monofluoroterphenyls to allow comparisons to be made (the homologues mainly prepared are the dipentyl-substituted, pentyl-, hexoxy-substituted and pentyl-, octoxy- substituted). Also, of course, the transition temperatures are of interest in their own right and can be compared with those of the terphenyls prepared by Chan (fluorine in the centre ring). No results for physical properties are available for these compounds, however, they are expected to be similar to those terphenyls with the lateral fluoro-substituent in the centre ring prepared by Chan.[127-130]

3.2 (a) (i) Transition Temperatures (°C) for Parent Terphenyls (compounds **296**,[36] **97** and **98**, Table 9, p 263)

Table 9

Transition Temperatures (°C) for 4-Alkoxy-4"-alkyl- and 4,4"-Dialkylterphenyls **(296,[36] 97 and 98)**



Compound			Transition Temperatures (°C)						
No.	R	R'	K		S_B		S_A		I
296	C_5H_{11}	C_5H_{11}	*	192.0	----------------		*	213.0	*
97	C_5H_{11}	$C_6H_{13}O$	*	205.0	*	216.0	*	228.5	*
98	C_5H_{11}	$C_8H_{17}O$	*	194.5	*	211.0	*	221.5	*

The transition temperatures for the parent systems of the chosen homologues reveal very high melting points (~200 °C) and as is usual the dialkyl system[36] (compound **296** mp

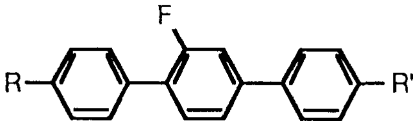
192.0 °C) is lower melting than the alkyl-alkoxy systems (compounds **97** and **98**, mp 205.0 and194.5 °C respectively). The dialkyl compound (**296**, $T_{SA\text{-}I}$ value 213.0 °C) exhibits only one mesophase (S_A) whereas the alkyl-alkoxy-substituted terphenyls (compounds **97** and **98**, $T_{SA\text{-}I}$ values 228.5 and 221.5 °C respectively) also have an S_B phase. All three parent systems have no tendency towards tilted smectic phases and have only small liquid crystal ranges. The lower melting and clearing point of the octoxy compound when compared to the hexoxy homologue is a trend typical of the other systems prepared (see later).

3.2 (a) (ii) Transition Temperatures (°C) for Lateral Monofluoro-substituted Terphenyls

(compounds **297-301**, Table 10, p 264; compounds **102**, **103**, **107** and **108**, Table 11, p 265 and compounds **110-112** and **119-121**, Table 12, p 266)

Table 10

Transition Temperatures (°C) for 4- or 4''- Alkoxy-4- or 4''- pentyl and 4,4''-Dipentyl- 2'-fluoroterphenyls **(297-301)** (all these compounds were prepared by L.K.M. Chan[127-130])



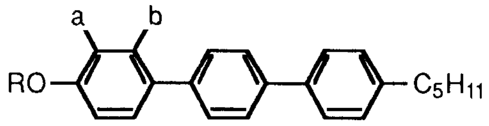
Compound			Transition Temperatures (°C)								
No.	R	R'	K	S_G	S_J	S_L	S_I	S_C	S_A	N	I
297	C_5H_{11}	C_5H_{11}	* 51.5	--------	--------	* 62.0	--------	--------	*109.5	*136.5	*
298	C_5H_{11}	$C_6H_{13}O$	* 70.0	* 78.0	--------	* 92.0	* 93.0	*118.0	*155.0	*166.5	*
299	C_5H_{11}	$C_8H_{17}O$	* 69.0	* 83.0	--------	*100.5	--------	*124.0	*158.0	*161.0	*
300	$C_6H_{13}O$	C_5H_{11}	* 62.5	--------	(* 47.5	--------	* 50.0)	*113.5	--------	*162.5	*
301	$C_8H_{17}O$	C_5H_{11}	* 47.0	--------	(* 40.0)	--------	* 53.5	*116.5	*130.0	*155.0	*

The transition temperatures for the monofluoroterphenyls prepared by Chan[127-130] (fluorine in the centre ring) have been included only for comparison with the systems reported here and so very little will be said of these systems except in other comparisons.

The most important and strikingly obvious effect of the monofluoro-substituent (regardless of its position) is the much reduced melting points (up to 140 °C) and the very wide range of liquid crystal phase types exhibited (especially the tendency towards tilted smectic mesophases). This wide range of phases makes individual phase-by-phase comparisons difficult but there are very many interesting trends which can be discussed.

Table 11

Transition Temperatures (°C) for 4-Alkoxy-4"-pentyl- 2- or 3-fluoroterphenyls (**102**, **103**, **107** and **108**)

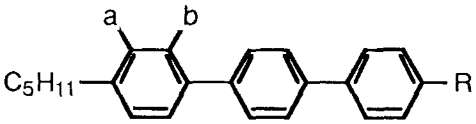


Compound				Transition Temperatures (°C)								
No.	R	a	b	K	S_K	S_G	S_J	S_B	S_C	S_A	N	I
102	C_6H_{13}	F	H	*	--------	*160.0	--------	--------	*162.0	*201.0	--------	*
103	C_8H_{17}	F	H	*	--------	*146.0	--------	*158.0	--------	*195.0	--------	*
107	C_6H_{13}	H	F	*83.5	(* 48.5	--------	* 62.0)	--------	*105.0	--------	*166.0	*
108	C_8H_{17}	H	F	*69.0	(* 25.0	--------	* 43.5)	--------	*119.0	--------	*158.0	*

The melting points do depend significantly on where the the fluoro-substituent is positioned. A monofluoro-substituent (except on the edge of the core) will cause a twist in the terphenyl system about the inter-annular bond adjacent to the fluorine atom. In the case of compounds **298**, **299**, **111**, **112** the untwisted biphenyl section is alkoxy-substituted and therefore their melting points (70.0, 69.0, 115.0, 102.0 °C respectively) are higher than for their isomeric systems (compounds **300**, **301**, **107**, **108**; mp 62.5, 47.0, 83.5, 69.0 °C respectively) which have an alkyl-substituted, untwisted biphenyl moiety. For the same reason the equivalent liquid crystal phase transition temperatures (where a common phase exists) are also higher for compounds **298**, **299**, **111**, **112** when compared with compounds **300**, **301**, **107**, **108** respectively. However, the differences for the two sets of compounds are much less for the mesophase transitions than for the melting points. In fact the clearing points ($T_{N\text{-}I}$ values) for all such comparable alkyl-alkoxy-substituted monofluoroterphenyls (compounds **298-301**, **107**, **108**, **111** and **112** are almost identical but the octoxy systems have lower clearing points (155.0-161.0 °C) than the hexoxy homologues (162.5-166.5 °C), which is usual.

Table 12

Transition Temperatures (°C) for 4''-Alkoxy-4-pentyl- and 4,4''-Dipentyl-2- or 3- fluoroterphenyls **(110-112** and **119-121)**



Compound				Transition Temperatures (°C)						
No.	R	a	b	K	S_G	S_I	S_C	S_A	N	I
110	C_5H_{11}	H	F	* 72.5	----------	----------	* 80.0	----------	* 136.0	*
111	$C_6H_{13}O$	H	F	* 115.0	----------	----------	* 131.5	----------	* 166.5	*
112	$C_8H_{17}O$	H	F	* 102.0	----------	(* 99.5)	* 137.5	----------	* 160.0	*
119	C_5H_{11}	F	H	*	* 156.5	----------	----------	* 185.5	----------	*
120	$C_6H_{13}O$	F	H	*	* 176.0	----------	----------	* 210.0	----------	*
121	$C_8H_{17}O$	F	H	*	* 170.5	----------	* 176.5	* 202.5	----------	*

In the case where the fluoro-substituent is part of the untwisted biphenyl moiety (*i.e.* fluorine in the centre ring, compounds **298-301**; mp 70.0, 69.0, 62.5, 47.0 °C) then melting points, and to a small extent mesophase transition temperatures, are lower than when the fluorine atom is in an end ring and not part of the untwisted biphenyl moiety (compounds **111, 112, 107, 108**; mp 115.0, 102.0, 83.5, 69.0 °C). The same point applies to the two dialkyl systems; compound **297** (mp 51.5 °C) is of lower melting point than compound **110** (mp 72.5 °C) but the clearing point ($T_{N\text{-}I}$ value) is identical (136.5 °C).

In the case of compounds **102, 103, 119-121** the fluoro-substituent occupies an outer core position and therefore cannot cause any inter-annular twisting. Accordingly, melting points would be expected to be much higher. For this reason, and the fact that the fluorine has more space around it (which leads to less molecular broadening), these compounds should give much higher mesophase transition temperatures (and therefore higher clearing points). Remarkably no melting points have been identified for such compounds. The DSC traces show only the mesophase to mesophase and mesophase to isotropic liquid transitions and are reversible on cooling; despite many reheats and cools and the use of new samples, no melting peaks (on heating) or recrystallisation peaks (on cooling to -20 °C) were seen. Optical microscopy also revealed no visible change for the sample until the S_G to S_X transition (S_X being the appropriate mesophase above the S_G phase). This perhaps indicates that the compounds are actually in the S_G phase at room temperature and below and, bearing in mind that the S_G phase is not really liquid crystalline but is a disordered crystal with no liquid properties (see Introduction, p 2), this is not unreasonable. However, such compounds would not be expected to have such low melting points when compared to the other compounds in the tables (see above). Possibly another explanation is of a very gradual 'melting' process to the disordered crystal state (S_G) which is not detected by the DSC [similar in principle to the tilt angle gradually changing in an S_C phase to give an S_A phase (zero tilt); such a transition is also not always revealed by DSC analysis].

The liquid crystal phase transition temperatures of compounds **102**, **103**, **119-121** are, as expected, much higher when compared to their analogues with the fluoro-substituent positioned inside the core. These compounds also do not have nematic phases and clear to the isotropic liquid from the S_A phase at ~200 °C (very high S_A thermal stability). In fact the fluoro-substituent in this outer core position has not had much of an effect and these compounds are somewhat of a compromise in character between the parent systems and the monofluoroterphenyls with the fluorine positioned inside the aromatic core.

3.2 (b) Lateral Non-*ortho*-Difluoro-substituted Terphenyls

This sub-section represents the first of much work on difluoroterphenyl systems (see also later) and these compounds were prepared to determine what effect a second lateral fluoro-substituent at a variety of positions in a terphenyl system would have on melting points and mesophase thermal stabilities (especially the effect on the S_C phase thermal stability). Systems of this type were prepared before the *ortho*-difluoroterphenyls because of the more straightforward, standard synthetic routes. No Physical property results are available from our collaborators at R.S.R.E. (Malvern) because they gave their full attention to the *ortho*-difluoro-substituted systems [see section 3.2 (c), p 273].

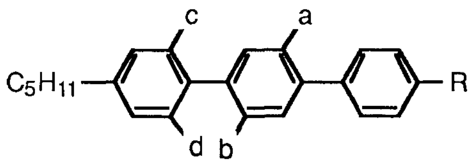
3.2 (b) (i) Transition Temperatures (°C) for Lateral Non-*ortho*-Difluoro-substituted Terphenyls (compounds **127**, **128**, **130** and **131**, Table 13, p 269 and compounds **136** and **138-140**, Table 14, p 269)

For difluoroterphenyls where the two fluoro-substituents are not *ortho* to each other two possibilities arise. Either the two fluorines are in one ring and are inherently fixed with one fluorine at each side of the molecule (Table 13, p 269) or the two fluorines are in different rings and therefore not fixed with respect to each other (Table 14, p 269). Obviously, for each difluoroterphenyl there are two monofluoroterphenyls with which it could be compared (except where the two fluoro-substituents occupy equivalent positions) and this complicates comparisons. Additionally, the consideration of differently substituted difluoroterphenyls gives many more comparisons.

The difluoro-compound **128** (mp 51.0 °C) has a lower melting point than either of its comparable monofluoroterphenyls (compounds **298** and **300**, mp 70.0 and 62.5 °C respectively), compound **131** (mp 61.0 °C) has a much lower melting point than its comparable compound (**111**, mp 115.0 °C) and compound **130** (mp 50.0 °C), similarly has a reduced melting point compared to compound **110** (mp 72.5 °C). Compound **127** (mp 63.0 °C), however, has a higher melting point than the monofluoro analogue (**297**, mp 51.5 °C) and this may be because the second fluorine has created a perfectly symmetrical molecule which allows better packing.

Table 13

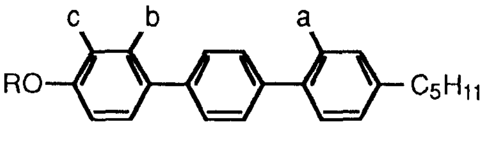
Transition Temperatures (°C) for 4-Pentyl- or 4-Hexoxy- 4''-pentyl-2',5'-difluoroterphenyls (**127** and **128**) and 4-Pentyl-4''-pentyl- or 4''-hexoxy-2,6-difluoroterphenyls (**130** and **131**)



Compound						Transition Temperatures (°C)				
No.	R	a	b	c	d	K		N		I
127	C_5H_{11}	F	F	H	H	*	63.0	*	85.5	*
128	$C_6H_{13}O$	F	F	H	H	*	51.0	*	117.0	*
130	C_5H_{11}	H	H	F	F	*	50.0	*	82.0	*
131	$C_6H_{13}O$	H	H	F	F	*	61.0	*	122.5	*

Table 14

Transition Temperatures (°C) for 4-Alkoxy-4''-pentyl-2,2''-difluoroterphenyls (**136** and **138**) and 4''-Alkoxy-4-pentyl-2,3''-difluoroterphenyls (**139** and **140**)



Compound					Transition Temperatures (°C)						
No.	R	a	b	c	K		S_C		N		I
136	C_6H_{13}	F	F	H	*	45.0	-----------------		*	131.0	*
138	C_8H_{17}	F	F	H	*	42.5	-----------------		*	121.5	*
139	C_6H_{13}	F	H	F	*	90.0	*	105.5	*	139.0	*
140	C_8H_{17}	F	H	F	*	75.5	*	107.0	*	132.0	*

Even lower melting points (45.0 and 42.5 °C) are seen for compounds **136** and **138** [these compounds can be compared with compounds **107** or **111** (mp 83.5 and 115.0 °C) and **108** or **112** (mp 69.0 and 102.0 °C) respectively] where the two fluorine atoms are sited in different rings and therefore not inherently fixed with respect to each other. Compounds **139** (mp 90.0 °C) and **140** (mp 75.5 °C) are similar to compounds **136** and **138**, respectively, in that the two fluorine atoms are placed in different rings, but one fluorine now occupies an outer core position and gives higher melting points, although the values are lower than those for comparable monofluoroterphenyls [compounds **111** and **112** (mp 115.0 and 102 °C)].

Mesophase thermal stability is well known to be reduced by fluoro-substitution[33,127-130,163,164,180] (numerous examples are seen in every section of this thesis) and a second fluoro-substituent in terphenyl systems has a dramatic effect on the liquid crystal behaviour.

Where the two fluorine atoms are inherently fixed at each side of the molecule (compounds **127**, **128** and **130**, **131**, Table 13, p 269) a broader molecule than the monofluoroterphenyl is produced. This has caused typical reductions (when compared to the appropriate monofluoroterphenyls) in the T_{N-I} values of ~45-50 °C which has brought the clearing points for this class of alkyl-alkoxy-substituted difluoroterphenyl down to ~120 °C from ~165 °C (clearing point values for the dialkyl-substituted terphenyls are ~ 35 °C lower). More importantly all the smectic phases seen in the monofluoroterphenyls have been eliminated, which, allowing for supercooling means that the smectic phase thermal stabilities have been reduced by at least 100 °C.

Where the two fluorine atoms are sited in different rings the net ('time averaged') increase in molecular breadth is not as great as for the above case and therefore for compounds **136** and **138** the T_{N-I} value reductions due to the second fluoro-substituent are not as great (~35 °C). Additionally, where the second fluorine atom is placed on the outer edge of the aromatic core (compounds **139** and **140**) the increase in molecular breadth is even less (also a fluorine in this outer core position does not cause inter-annular twisting) and consequently the reductions in T_{N-I} values are only 27.5 and 28.0 °C (compared with compounds **111** and **112** respectively). However, the other way of comparing compounds **139** and **140** with monofluoroterphenyls is by considering the effect of a second fluoro-substituent inside the core (*i.e.* where the first fluorine atom was sited on the outer edge of the core). This is obviously going to increase molecular breadth considerably (as well as causing an inter-annular twist which was not present in such monofluoroterphenyls) and this correspondingly reduces the liquid crystal phase thermal stability of compounds **139** and **140** when compared to compounds **102** and **103** respectively. The clearing points (monofluoroterphenyls **102** and **103** have T_{SA-I} values and not T_{N-I} values) for the above comparisons have been reduced by around 60 °C. The positioning of one of the two fluorine atoms in compounds **139** and **140** on the outer edge of the aromatic core has preserved the S_C character of the monofluoroterphenyls **111** and **112** with reduced thermal stability values of 26.0 and 30.5 °C respectively. However, the ordered smectic phases of compounds **102** and **103** have been completely eliminated by the siting of the second fluoro-substituent inside the core. The location of both fluorine atoms inside the core (compounds **136** and **138**) has eliminated all smectic tendencies (and allowing for supercooling, this means that the S_C phase thermal stability has been reduced by at least 100 °C compared to compounds **107, 111** and **108, 112** respectively).

Comparison between the different types of difluoroterphenyls clearly shows that (a) where the two fluorines are in different rings within the terphenyl core (Table 14, p 269) particularly low melting points are seen (~45 °C), (b) where the two fluorines are inherently fixed one either side of the core (Table 13, p 269) higher melting points result (~50-60 °C), (c) positioning one of the two fluoro-substituents on the outer edge of the core (Table 14, p 269) leads to higher melting points (~75-90 °C). The effect on liquid crystal phase thermal stabilities is also very clear. Compounds with broader molecules (*i.e.* compounds with one fluorine atom inherently fixed either side of the molecules; Table 13, p 269) have particularly low T_{N-I} values (~80-85 °C for the dialkyl systems and ~120 °C for the alkoxy-alkyl systems). The narrower type of molecule of the alkoxy-alkyl-substituted type (compounds **136** and **138**) gives higher T_{N-I} values (~120-130 °C). However, both these types of compound do not exhibit smectic phases and are purely nematogenic in character.

For the difluoroterphenyls with one fluoro-substituent located on the outer edge of the core (compounds **139** and **140**), a special situation arises because this position causes no inter-annular twists within the core and has more space around it (narrower molecules). For this reason, the T_{N-I} values are fairly high at around 135 °C but not a great deal higher than for compounds **136** and **138**. However, it is the high S_C thermal stability (105.5 and 107.0 °C for compounds **139** and **140** respectively), caused by this outer edge fluoro-substituent, that is important; despite low melting points compounds **136** and **138** show no smectic tendency.

The behaviour of the non-S_C exhibiting compound **128** was examined by mixing small amounts of the compound (~5-15%) with two of Chan's monofluoroterphenyls (see p 273). The work revealed that these small amounts totally eliminated the ordered smectic phases below the S_C phase whilst only slightly depressing the thermal stabilities of the S_C, S_A and nematic phases (see Table 15).

Table 15

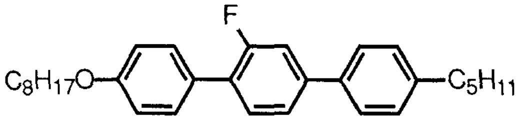
Transition Temperatures (°C) for Mixtures of Compound 128 in Host Materials

F8O.5T and F9.3T

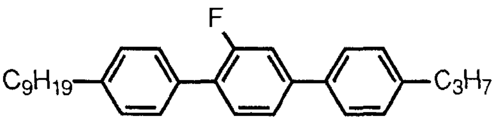
Composition	K	S_J	S_I	S_C	S_A	N	I
100% **F8O.5T**	* 47.0	(* 40.0)	* 53.5	* 116.5	* 130.0	* 155.0	*
94% **F8O.5T** 6% **128**	* 50.0 (27.5)	----------	----------	* 113.0	* 122.0	* 152.5	*
90% **F8O.5T** 10% **128**	* 48.0 (23.0)	----------	----------	* 109.5	* 113.0	* 150.5	*

Composition	K	S_B	S_C	S_A	N	I
100% **F9.3T**	* 46.0	(* 35.0)	* 52.0	* 89.0	* 126.5	*
95% **F9.3T** 5% **128**	* 43.5 (8.0)	------------	* 50.0	* 72.0	* 125.0	*
84% **F9.3T** 16% **128**	* 41.0 (8.0)	------------	* 48.0	* 60.0	* 125.0	*

This work was substantiated by subsequent work carried out by our collaborators at R.S.R.E. (Malvern).



F8O.5T



F9.3T

Summary of Sub-section 3.2 (b) (i)

The difluoroterphenyls discussed so far are generally lower melting than their monofluoroterphenyl analogues and their mesophase thermal stability is dramatically reduced when compared to monofluoroterphenyls. The degree of this reduction appears to be dependent on the broadness of the molecule and, to some extent, on the number of fluorine-induced inter-annular twists. Where one of the two fluorine atoms is placed on the outer edge of the terphenyl core then an S_C phase is induced with quite high thermal stability.

The mixture work involving the non-S_C exhibiting materials with monofluoroterphenyls shows the ability of difluoroterphenyls to eliminate ordered smectic phases and to support S_C, S_A and nematic phases.

3.2 (c) Lateral *ortho*-Difluoro-substituted Terphenyls and Some Biphenyl Analogues[164]

The previous work on difluoroterphenyls paved the way for this extensive programme on the synthesis of *ortho*-difluoro-substituted aromatic systems and an assessment of their suitability for use as host materials in ferroelectric (S_C*) mixtures. As shown in the previous sub-section a narrower molecule maintains the mesophase thermal stability more effectively. Therefore, the best difluoro-substitution pattern would be where the two substituents are next (*ortho*) to each other. This means that both the fluorine atoms are inherently fixed on one side of the molecule, giving molecules which are almost identical in breadth to their monofluoroterphenyl analogues; and so mesophase thermal stability should be upheld. Fixing both the fluoro-substituents on one side of the molecule has another great advantage in that an increased lateral dipole will result and consequently this will lead to a more negative dielectric anisotropy ($-\Delta\varepsilon$) (which is proportional to the square of the dipole). This higher $-\Delta\varepsilon$ value will have been achieved with no further protrusion of groups on the side of the molecules which should mean no increase in viscosity values (which may be lower due to the smoothing effect of the two substituents) compared to the monofluoroterphenyls. This combination of beneficial features will be a very important breakthrough as there is great difficulty in producing compounds with high negative dielectric anisotropy ($-\Delta\varepsilon$) which have reasonably low viscosity values and high S_C phase thermal stability. The difficulty arises because lateral groups are required to give a lateral dipole to ensure $-\Delta\varepsilon$ values. Such groups protrude from the core and a large dipole is required to counter the positive dielectric anisotropy of the aromatic core and to give a net $-\Delta\varepsilon$ (*e.g.* cyano-substituent, see p 291 for discussion of lateral cyano-substituted terphenyls). This protrusion leads to high viscosities (which give lower switching speeds and counter the negative $\Delta\varepsilon$) and the resulting broader molecule reduces the S_C phase thermal stability.

The use of a small lateral polar group of high electronegativity (fluorine) seems the ideal answer, except that one fluorine is only sufficient to counter the $+\Delta\varepsilon$ contribution from the terphenyl core. Hence the use of a second fluoro-substituent *ortho* to the first to gain the advantages discussed above.

A smaller number of *ortho*-difluoro-substituted biphenyls were prepared in the expectation that they would be much lower melting and hopefully not depress the S_C phase thermal stability of ferroelectric mixtures too greatly. If this were so then they would be useful additives for ferroelectric mixtures because having one aromatic ring less than their terphenyl analogues would give a lower birefringence, a lower viscosity and probably higher negative values of dielectric anisotropy.

Another useful way of lowering birefringence is to replace one of the aromatic rings of the terphenyl system with a *trans*-substituted cyclohexane ring. This approach enables mesophase thermal stability to be maintained (albeit with higher melting points) when compared to the simple straight chain biphenyls systems referred to above. However such compounds do have a tendency towards the S_B mesophase at the expense of the S_C phase.[33,225] Such compounds could still make useful additives for ferroelectric mixtures provided that any S_B phase does not prevail in the mixture. Compounds **199, 205, 209** and **213** were prepared to test this possibility but in effect they are *ortho*-difluoro-substituted biphenyls which incorporate a cyclohexyl moiety as part of the alkyl or alkoxy chain.

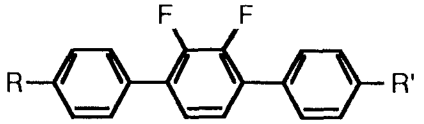
The synthesis of compounds in this section has already been detailed (p 222) and the results and conclusions are discussed below.

3.2 (c) (i) Transition Temperatures (°C) for Lateral *ortho*-Difluoro-substituted Terphenyls

(compounds **147-152**, Table 16, p 275; compounds **159-161**, **187**, Table 17, p 278; compounds **175-181**, **186**, Table 18, p 280; compounds **188**, **190**, Table 19, p 285)

Table 16

Transition Temperatures (°C) for 4-Alkoxy-4''-alkyl- and 4,4''-Dialkyl- 2',3'-difluoroterphenyls **(147-152)**



Compound			Transition Temperatures (°C)								
No.	R	R'	K		S_C		S_A		N		I
147	C_5H_{11}	$C_6H_{13}O$	*	54.0	*	67.0	---------------		*	149.0	*
148	C_5H_{11}	$C_8H_{17}O$	*	48.5	*	95.0	---------------		*	141.5	*
149	C_5H_{11}	C_5H_{11}	*	60.0	-------------------------------				*	120.0	*
150	C_5H_{11}	C_7H_{15}	*	36.5	(*	24.0)	---------------		*	111.5	*
151	C_5H_{11}	C_9H_{19}	*	42.5	*	66.0	---------------		*	110.0	*
152	C_9H_{19}	C_7H_{15}	*	49.0	*	77.0	*	93.0	*	108.5	*

The first of this class of compound to be prepared were those with the *ortho*-difluoro moiety in the centre ring (compounds **147-152**, Table 16, p 275). Some of these compounds can be compared directly with the monofluoroterphenyls prepared by Chan[127-130] (compounds **297-301**, Table 10, p 264) and with the non-*ortho*-difluoroterphenyls previously discussed (compounds **127** and **128**, Table 13, p 269).

The melting points of the alkyl-alkoxy-substituted compounds **147** and **148** are quite low (54.0 and 48.0 °C respectively). Each of these compounds has two directly comparable monofluoroterphenyls [compounds **298** (mp 70.0 °C), **300** (mp 62.5 °C) and **299** (mp 69.0 °C), **301** (mp 47.0 °C) respectively] which are generally slightly higher melting. The dialkyl compound (**149**), however, melts at 60.0 °C (higher than alkyl-alkoxy compounds **147** and **148**) and this is higher than for the comparable monofluoroterphenyl (compound **297**, mp 51.5 °C). This higher than expected melting point is due to the molecules being totally symmetrical (see also the comparison of compound **127**, mp 63.0 °C with compound **297**).

The unsymmetrical dialkyl-substituted systems (no monofluoroterphenyls are available for comparison) of this type (compounds **150-152**) with longer and different alkyl chains melt considerably lower (see later for full discussion). These lower melting points combined with the effect from the longer alkyl chains give rise to an S_C mesophase which increases in thermal stability with increasing molecular length (as does the melting point). The T_{N-I} values, however, decrease slightly with the increasing molecular length and for the longest alkyl chain system (the C_9/C_7 homologue, compound **152**) an S_A phase is seen. The high melting, symmetrical compound (**149**) is purely nematic in character; this is possibly due to the high melting point masking the S_C phase and our collaborators at R.S.R.E. (Malvern) find that, in ferroelectric mixtures, this compound behaves as though the S_C phase thermal stability is very high (greater than 60 °C). Interestingly, the monofluoroterphenyl analogue (compound **297**), although highly smectic, does not exhibit an S_C phase either. As expected the alkoxy-alkyl-substituted difluoroterphenyls (compounds **147** and **148**) have much higher smectic phase thermal stabilities and this is represented purely as the S_C phase. The T_{N-I} values are also much higher than for the dialkyl-substituted analogues.

The T_{N-I} values of compounds **147** and **148** (149.0 and 141.5 °C respectively) are reduced by around 15.0 °C when compared to the four analogous monofluoroterphenyls (compounds **298-301**). This small T_{N-I} depression is due to the second fluoro-substituent not broadening the molecules significantly and it contrasts with the large depressions in

T_{N-I} values of ~45 °C which are seen when the two fluoro-substituents are fixed one either side of the molecules (sub-section 3.2 (b) (i), p 268). A similar reduction in the T_{N-I} value is seen for the dialkyl derivative (compound **149**, T_{N-I} value 120.0 °C) when compared to the monofluoro system (compound **297**, T_{N-I} value 136.5 °C).

For compounds **147** and **148** the S_C phase thermal stability has been reduced (by 51.0 and 46.5 °C **147/298** and **147/300** respectively and by 29.0 and 21.5 °C **148/299** and **148/301** repectively) to 67.0 and 95.0 °C repectively with no S_A tendency when compared with compounds **298-301**. The thermal stabilities of all the ordered smectic phases have been reduced by much greater amounts by the second fluorine because they have been totally eliminated (as has similarly occurred for compound **149** when compared with compound **297**). The lower melting point, higher T_{SC-N} value and lower T_{N-I} value of the octoxy-substituted compound (**148**) when compared to the hexoxy-substituted homologue is typical; as well as being widespread throughout this work, the trend is also revealed in Chan's work on central-ring-monofluoroterphenyls.[127-130]

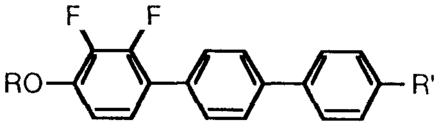
The melting points of these compounds are similar to those for the non-*ortho*-difluoroterphenyls where both the fluoro-substituents are inside the core (sub-section 3.2 (b) (i), p 268); the narrow molecule has, however, given rise to compounds with usefully high S_C phase thermal stabilities (especially compound **148**). This class of *ortho*-difluoroterphenyls (with fluorines in the centre ring) are also very strongly nematic in character.

For those compounds with the two *ortho*-fluoro-substituents in an end ring there are two possible types reported here: the *ortho*-difluoro unit can be part of an alkoxy-substituted end ring with the other end ring being only alkyl-substituted (compounds **159-161** and **187**, Table 17, p 278; dialkoxy compounds of this type were not prepared) or the *ortho*-difluoro moiety can be part of an alkyl-substituted end ring with the other end ring being either alkoxy- or alkyl- substituted (compounds **175-181** and **186**, Table 18, p 280). Generally, these types of difluoroterphenyls have higher melting points, much greater smectic tendency (particularly S_C, with high thermal stabilities and wide ranges) and smaller nematic phase ranges (but much higher T_{N-I} values) than those compounds with the *ortho*-fluoro moiety in the central ring.

It has already been shown for compounds **139** and **140** that a fluoro-substituent on the edge of the core gives higher melting points than when positioned inside the core and, although no melting points have been detected for monofluoroterphenyls with the fluoro-substituent on the edge of the core, they are expected to be very high (in keeping with their high mesophase thermal stabilities).

Table 17

Transition Temperatures (°C) for 4-Alkoxy-4"-alkyl-2,3-difluoroterphenyls **(159-161 and 187)**



Compound			Transition Temperatures (°C)								
No.	R	R'	K		S_C		S_A		N		I
159	C_6H_{13}	C_5H_{11}	*	97.5	*	145.5	---------------		*	166.0	*
160	C_8H_{17}	C_5H_{11}	*	93.5	*	144.0	*	148.0	*	159.0	*
161	C_8H_{17}	C_7H_{15}	*	89.5	*	148.0	*	151.5	*	154.0	*
187	C_8H_{17}	4MH‡	*	72.0	*	120.0	---------------		*	128.0	*

‡ = (±)-4-methylhexyl

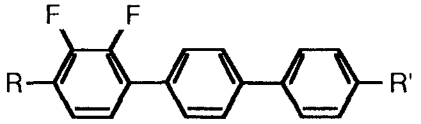
Compounds **159** and **160** with an *ortho*-difluoro unit as part of an alkoxy-substituted end ring (mp 97.5 and 93.5 °C respectively) have higher melting points than their monofluoroterphenyl analogues whose fluorine is within the core (compounds **107** and **108**, mp 83.5 and 69.0 °C respectively); this might have been expected since the second fluoro-substituent has been placed on the outer edge of the core. What is remarkable, though, is that the outer core second fluorine has increased the S_C phase thermal stabilities to 145.5 and 144.0 °C (compounds **159** and **160** respectively) from the 105.0 and 119.0 °C of the comparable monofluoroterphenyls (compounds **107** and **108** respectively) with an S_A phase being induced in the longer octoxy-substituted compound

(**160**). The more ordered smectics (below the S_C phase) seen in the monofluoroterphenyls are no longer a feature of these difluoroterphenyl analogues. The T_{N-I} values of the difluoroterphenyls are 166.0 and 159.0 °C (compounds **159** and **160**) and can be considered to be identical to the 166.0 and 158.0 °C for their monofluoro-substituted equivalents (compounds **107** and **108**). Comparison of compounds **159** and **160** with their other possible monofluoroterphenyls (compounds **102** and **103**) is less precise due to the undetected melting points and to the absence of nematic phases (and of an S_C phase for compound **103**). However, from this point of view the second fluoro-substituent has been placed inside the core and as expected reduces the smectic tendency considerably (~50 °C). However this is not a direct comparison due to the monofluoroterphenyl compounds' tendencies towards the S_A phase (and ordered smectic phases) whereas the difluoroterphenyl analogues are highly S_C; the ordered S_G and S_B phases of compounds **102** and **103** have been completely eliminated by the second fluoro-substituent.

A similar comparison can be made for compounds **176** and **177** (*ortho*-difluoro moiety in an alkyl-substituted end ring). However, their melting points (101.5 and 89.5 °C respectively) are lower than their most comparable monofluoroterphenyl analogues (compounds **111** and **112**, mp 115.0 and 102.0 °C respectively). The effect of the second fluorine has again been to increase the smectic tendency by ~35 °C although for compounds **176** and **177** an S_A range of around 10 °C has been induced, with the S_C phase still predominating. The T_{N-I} values have risen by 5.0 and 6.0 °C for compounds **176** and **177** to 171.5 and 166.0 °C respectively. Compared to their other analogues (monofluoroterphenyls **120** and **121**), compounds **176** and **177** have reduced smectic tendency revealing a nematic phase and no tendency towards the ordered S_G phase seen in compounds **120** and **121**. The dialkyl compound (**175**) shows a higher melting point (81.0 °C) than its comparable monofluoroterphenyl (**110**, mp 72.5 °C). As seen above for the alkoxy-alkyl-substituted systems (compounds **176** and **177**), the dialkyl system (**175**) has increased smectic tendency compared to **110**) caused by the outer core fluoro-substituent (S_C thermal stability has increased by 35.5 °C to 115.5 °C and the T_{N-I} value has increased by just 6.0 °C to 142.0 °C). Compared to the other

Table 18

Transition Temperatures (°C) for 4"-Alkoxy-4-alkyl- and 4,4"-Dialkyl- 2,3-difluoroterphenyls (**175-181** and **186**)



Compound			Transition Temperatures (°C)										
No.	R	R'	K		S_I		S_C		S_A		N		I
175	C_5H_{11}	C_5H_{11}	*	81.0	------------		*	115.5	*	131.5	*	142.0	*
176	C_5H_{11}	$C_6H_{13}O$	*	101.5	------------		*	156.5	*	167.0	*	171.5	*
177	C_5H_{11}	$C_8H_{17}O$	*	89.0	------------		*	155.5	*	165.0	*	166.0	*
178	C_5H_{11}	C_7H_{15}	*	65.5	*	74.5	*	118.5	*	135.0	*	137.0	*
179	C_7H_{15}	C_5H_{11}	*	56.0	------------		*	105.5	*	131.0	*	136.0	*
180	C_9H_{19}	C_3H_7	*	63.0/80.0	------------		*	84.5	*	117.0	*	131.5	*
181	C_9H_{19}	C_7H_{15}	*	44.0	*	55.0	*	105.0	*	127.0	------------		*
186	C_5H_{11}	4MH‡	*	64.0	------------		*	86.0	------------		*	100.5	*

‡ = (±)-4-methylhexyl

monofluoroterphenyl (**119**), the difluoro system has a lower smectic tendency by 54.0 °C at 131.5 °C but the monofluoro system has no S_C phase whereas the difluoroterphenyl analogue (compound **175**) is strongly S_C in nature.

To conclude comparisons of the difluoroterphenyls with their monofluoro analogues it is worth summarising the main points of advantage of the *ortho*-difluoro systems. Although melting points are little reduced by the addition of a second fluoro-substituent, the effect of the second fluoro-substituent on the types of mesophase and their thermal stabilities has been miraculous. The main effect has been the total elimination of the ordered smectic phases, and the S_C and N phases in many cases take over from a strong S_A phase. The S_C tendency of the inner core monofluoro-substituted terphenyls has been fine-tuned to give *ortho*-difluoro-substituted compounds which in eutectic mixtures should give low melting points and wide S_C ranges (with small S_A and N ranges above to facilitate perfect alignment). From this transition temperature point of view these difluoroterphenyls should prove to be highly suited as host materials for ferroelectric (S_C*) mixtures for use in display devices or fast switching shutter devices.

The following is a discussion of the different types of *ortho*-difluoroterphenyls and and involved are those homologues for which no monofluoroterphenyl comparison was possible.

The compounds containing the two fluorines in the centre ring have much lower melting points and lower phase transition temperatures than their analogues with fluorines in either end ring. In particular, the S_A and S_C phases are strongly promoted by the two fluorines being in either end ring and large S_C ranges are found in these compounds.

The dialkyl compound **149** is solely nematogenic and because it is symmetrical it has a high melting point (60.0 °C), whereas compounds **147** and **148**, which are alkyl-alkoxy systems have lower melting points (54.0 °C and 48.5 °C respectively), and they also exhibit both an S_C phase which has a moderate range and a larger range nematic phase. The unsymmetrical dialkyl compounds **150, 151** and **152** show much lower melting points (36.5 °C, 42.5 °C and 49.0 °C respectively) than compound **149** and the larger size of the alkyl groups encourages S_C character with some S_A tendency as shown in compound **152**. This increase in smectic tendency is at the expense of the nematic phase stability as the clearing points ($T_{N\text{-}I}$ values) are around 10.0 °C lower than for compound **149**. The octoxy group of compound **148** lowers the melting point, raises the $T_{S_C\text{-}N}$ value and lowers the $T_{N\text{-}I}$ value as compared to the hexoxy-compound **147**. Other examples of this lowering of melting point and raising of smectic tendency in moving from hexoxy to octoxy have already been discussed and more will be seen later.

For the higher melting difluoroterphenyls with fluorines in the outer rings, it can be seen that in general they have much greater smectic tendency (particularly S_C, with large ranges) and smaller nematic ranges (but much higher $T_{N\text{-}I}$ values) than those compounds with fluorines in the centre ring. Compound **149** with fluorines in the centre ring has no smectic phases but a 60 °C nematic range whereas compound **175** has S_C and S_A phases with only a 10.5 °C nematic range. The position is clearer when we compare compounds **147** and **148** with isomeric compounds **159** and **160** respectively and with compounds **176** and **177** respectively. When the two fluorines are in an alkoxy-substituted end ring (with an alkyl-substituent in the other end ring; compounds **159** and **160**) then S_C thermal stability is increased by 78.5 °C (compound **159** compared to **147**) and by 49.0 °C (compound **160** compared to **148**) but nematic thermal stability is increased by only 17.0 °C and 17.5 °C respectively.

The series of compounds **159-161** is quite interesting: as usual, the C_8O/C_5 homologue (**160**) when compared to the C_6O/C_5 homologue (**159**) is slightly lower melting (93.5 vs. 97.5 °C), of higher smectic tendency (148.0 vs. 145.5 °C, although compound **160** has an S_A phase above the S_C phase) and of lower nematic phase thermal stability (159.0 vs. 166.0 °C). For compound **161** (C_8O/C_7 homologue) this is taken even further providing a usefully lower melting point (89.5 °C) with the benefit of a very wide S_C range and small S_A and nematic ranges (3.5 and 2.5 °C respectively).

When the two fluorines are in the alkyl-substituted end ring (with an alkoxy-substituent in the other end ring; compounds **176** and **177**) the smectic phases have even greater thermal stability compared to compounds **147** and **148**, with an S_A phase beginning to appear (ranges ~10 °C). The S_C thermal stabilities are increased by 89.5 °C (compound **176**) and by 60.5 °C (compound **177**) but the increases in nematic thermal stabilities are less at 22.5 °C and 24.5 °C respectively.

Mesophase stabilities are higher for compounds **176** and **177**, when compared to compounds **159** and **160**, because the former compounds have an unsubstituted, untwisted alkoxybiphenyl unit which allows greater molecular polarisability whereas compounds **159** and **160** just have an alkylbiphenyl unit. Since the melting points for these compounds are similar (within the range 89.0 °C to 101.5 °C), compounds **176** and **177** have larger S_C ranges (55.0 and 66.5 °C respectively) and both have the additional benefit of small (~10 °C) S_A and very small (~1 °C) nematic ranges.

Dialkyldifluoroterphenyls (compounds **175** and **178-181**) with the two fluorines in an end ring, as expected, have reasonably low melting points and the highest melting point (81.0 °C), for compound **175**, is perhaps accounted for by the alkyl chains being identical; compound **178** with unsymmetrical terminal groups, melts 15.5 °C lower. The $T_{SC\text{-}SA}$ value of compound **178** has increased by 3.0 °C to 118.5 °C, the $T_{SA\text{-}N}$ value has increased by 3.5 °C to 135.0 °C and the $T_{N\text{-}I}$ value has decreased by 5.0 °C to 137.0 °C. Compound **179** melts even lower, but the S_C tendency is also lowered (by 13.0 °C) and the $T_{N\text{-}I}$ value is similar to compound **178**. This has occurred because compound **179** has the shorter C_5 alkyl chain as part of the untwisted biphenyl section of the terphenyl with the longer (C_7) alkyl chain as part of the difluoro-substituted end ring, whereas compound **178** has the reverse situation. This is supported up by the very low S_C tendency ($T_{SC\text{-}SA}$ value of 84.5 °C) for compound **180** with a very short (C_3) alkyl chain as part of the untwisted biphenyl section and a very long (C_9) alkyl chain as part of the difluoro-substituted end ring; yet the $T_{N\text{-}I}$ value is very similar to those of compounds **178** and **179**. Compound **181** has two long alkyl chains and, although the shorter (C_7) alkyl chain is part of the untwisted biphenyl section, this give quite low S_C thermal stability (105.0 °C, which is similar to that for compound **179**). The overall long length of compound **181** has led to the loss of the nematic phase.

Where a long (C_7) alkyl chain is part of the untwisted biphenyl section of the terphenyl (*i.e.* compounds **178** and **181**) then the smectic tendency is great enough for an S_I phase to be seen. The S_I tendency is reduced by making the other alkyl chain long and therefore reducing the imbalance in the chain lengths. Compound **178** with a C_5 alkyl chain as part of the difluoro-substituted end ring has a $T_{SI\text{-}SC}$ value of 74.5 °C, however, when replaced by a C_9 alkyl chain the $T_{SI\text{-}SC}$ value has fallen by 19.5 °C to 55.0 °C. It would appear that a higher S_C thermal stability is encouraged by a longer alkyl chain being part of the untwisted biphenyl section of the terphenyl with a shorter alkyl chain being part of the *ortho*-difluoro-substituted end ring. Unfortunately, the S_I phase is also promoted by this arrangement of alkyl chains. The S_I phase of both compounds **178** and **181** was revealed by DSC analysis and was identified by optical microscopy making use of the free-standing film technique (see Introduction, p 21). The fact that the ordered S_I phase is found in dialkyl compounds and yet not found in the alkoxy-alkyl-substituted systems (*e.g.*

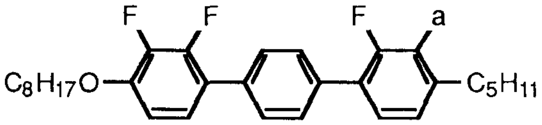
compounds **159-161, 176** and **177**) where it might have been more expected (due to greater polarisability) is very strange. It could be that the higher melting point of these compounds may just be masking the appearance of this ordered, tilted smectic phase (S_I phase). However if compound **178** is compared to compound **161** the melting point of compound **161** is only 24.0 °C higher and its S_C thermal stability is 29.5 °C higher. The S_I phase thermal stability would only have to be 15.0 °C higher than that for compound **178** for it to be seen enantiotropically in compound **161**; so another explanation is required. It could be that the lone pairs on the oxygen atom of the alkoxy chain cause intermolecular repulsion preventing the ordering required for the formation of an S_I phase yet making little difference to the more stable crystal state. This prevention of ordering may make no difference to the less ordered phases (S_C, S_A, N) and outweigh any enhancement of the S_I phase stability caused by increased polarity/polarisability. These compounds generally give a good compromise of low melting points and high $T_{SC\text{-}SA}$ values, however compound **151** with the two fluorines in the centre ring has a very low melting point (42.5 °C) and a respectable $T_{SC\text{-}N}$ value of 66.0 °C.

In an effort to reduce melting points further without any loss of S_C character, two compounds (**186** and **187**) with a (±)-4-methylhexyl (4MH) substituent were prepared. However, if the values for compound **186** are compared with those for compound **178** it is clear that this approach has not been successful. A small fall in melting point (1.5 °C) has been achieved but S_C thermal stability has been greatly reduced (32.5 °C) and the S_A phase has been lost giving a larger nematic range but a reduced $T_{N\text{-}I}$ value (by 36.5 °C). Compound **187** can be compared to compound **161** and the reduction in melting point of 17.5 °C is significant but less than the reduction in S_C character of 28.0 °C; again the S_A phase has been lost to leave a larger nematic range with a 26.0 °C lower $T_{N\text{-}I}$ value.

Compounds **188** and **190** are a trifluoroterphenyl and a tetrafluoroterphenyl respectively (see Table 19, p 285) and can be compared with compound **160** and with each other to see the effect of additional fluoro-substitution; compound **190** can also be compared with compound **177**. The additional fluorine of compound **188** compared to compound **160** has reduced the melting point by 35.5 °C but S_C character has been affected much more markedly and has been lowered by 82.5 °C. The loss of the S_A phase has given a compound of large nematic range (58.0 °C) with a T_{N-I} value (119.5 °C) reduced by 39.5 °C. The tetrafluoroterphenyl (**190**) has a much increased melting point over compound **188** (three fluorines) but this is not much higher than either of the difluoro compounds (**160** and **177**). The T_{N-I} value is much the same as for the trifluoro compound (**188**) which is as expected since the fourth fluorine is positioned on the edge of the core. The fact that the T_{N-I} value of compound **188** has not been decreased by the fourth fluorine of compound **190** (in fact it has increased by 1.0 °C) is an example substantiating other earlier observations that where the additional fluoro-substituent exerts no additional broadening or twisting of the molecules (*i.e.* simply filling up space within the molecular boundary) smectic and nematic phase thermal stabilities can be increased.[33,226,227] The fact that the S_C phase has disappeared altogether in compound **190** is probably due to the masking effect caused by the high melting point.

Table 19

Transition Temperatures (°C) for 4-Octoxy- 2,3,2"-trifluoro- and 2,3,2",3"-tetrafluoro- 4"-pentylterphenyls (**188** and **190**)



Compound		Transition Temperatures (°C)						
No.	a	K		S_C		N		I
188	H	*	58.0	*	61.5	*	119.5	*
190	F	*	111.5	---------------		*	120.5	*

Summary of Sub-section 3.2 (c) (i)

(a) Compounds with identical alkyl chains (compounds **149** and **175**) have higher melting points than some alkoxy-alkyl compounds.

(b) Alkyl-alkoxy compounds generally have higher melting points and higher phase transition temperatures than dialkyl systems.

(c) Compounds with the two fluorines in the end rings rather than in the centre ring have higher melting points and higher phase transition temperatures with greater smectic tendency.

(d) Compounds with the two fluorines in the centre ring tend to be more nematic in character, although alkyl-alkoxy compounds of this type do have reasonable S_C thermal stabilities. S_C character is introduced into dialkyl compounds of this type by unsymmetrical alkyl chains; an S_A phase is introduced by long alkyl chains.

(e) An octoxy group reduces melting point, increases S_C character and reduces nematic character when compared to a hexoxy group.

(f) A third fluorine seems to lower melting point but S_C and nematic thermal stabilities are reduced by a similar magnitude and the S_A phase is removed.

(g) A fourth fluoro-substituent raises the melting point significantly which leads to the loss of smectic phases. The T_{N-I} value is unaffected by the substitution of the fourth fluorine.

Physical property results of these compounds are discussed on p 298.

3.2 (c) (ii) Transition Temperatures (°C) for Lateral *ortho*-Difluoro-substituted Biphenyls (compounds **191-195**, Table 20, p 287; compounds **199** and **205**, Table 21, p 288 and compounds **209** and **213**, Table 22, p 288)

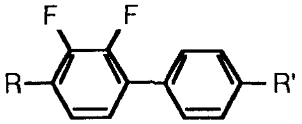
In the biphenyls the *ortho*-difluoro-substituents obviously have to be in an end ring. As for the terphenyls, where the unfluorinated section contains an alkoxy group the phase transition temperatures are higher and the compounds have greater smectic tendency (illustrated by the comparison of compound **193** with compound **191**). The melting point of compound **193** (mp 8.0 °C) is lower than that of compound **191** (mp 14.0 °C) and it has enantiotropic S_A (thermal stability of 12.0 °C) and nematic phases (T_{N-I} value 18.0 °C) whereas compound **191** just shows a monotropic nematic phase (with a thermal stability of 13.5 °C).

A longer alkyl chain in conjunction with an octoxy group greatly enhances phase transition temperatures although melting points are also increased. Compounds **195** and

192 have similar melting points (~25 °C) and both show S_C, S_A and nematic phases but the thermal stabilities of each of these phases (11.5, 33.0 and 34.0 °C for S_C, S_A and nematic respectively) are greater in compound **195** which has the octoxy group in an unsubstituted ring. Although not a direct comparison, compound **192** (octoxy group in the *ortho*-difluoro-substituted ring) has respective thermal stability values of 6.0, 13.0 and 23.0 °C. As expected, the dialkyl compound **194** does not show any liquid crystal phases at all and has a very low melting point (0.5 °C).

Table 20

Transition Temperatures (°C) for 4- or 4'- Alkoxy- 4'- or 4- Alkyl- and 4,4'-Dialkyl- 2,3-difluorobiphenyls **(191-195)**



Compound			Transition Temperatures (°C)								
No.	R	R'	K		S_C		S_A		N		I
191	$C_8H_{17}O$	C_5H_{11}	*	14.0	----------	----------	----------	----------	(*	13.5)	*
192	$C_8H_{17}O$	C_7H_{15}	*	24.0	(*	6.0	*	13.0	*	23.0)	*
193	C_5H_{11}	$C_8H_{17}O$	*	8.0	----------	----------	*	12.0	*	18.0	*
194	C_7H_{15}	C_5H_{11}	*	0.5	----------	----------	----------	----------	----------	----------	*
195	C_9H_{19}	$C_8H_{17}O$	*	25.0	(*	11.5)	*	33.0	*	34.0	*

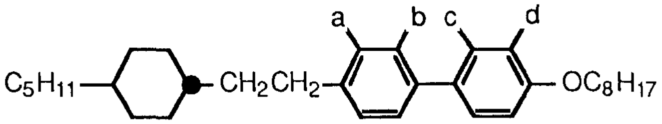
Compared with the terphenyls, these biphenyls have lower melting points and greatly reduced liquid crystal thermal stabilities, but the five compounds in Table 20 (p 287) do constitute a most interesting group of very low melting mesogens, two of which show enantiotropic mesophases.

The only biphenyl exhibiting an S_C phase which can be directly compared to a terphenyl is compound **192**, which has a 65.5 °C lower melting point than compound **161**, but much larger reductions in liquid crystal thermal stabilities are seen; down by 142.0, 138.5 and 131.0 °C for S_C, S_A and nematic respectively. Similar reductions in going from a terphenyl to a biphenyl are seen in other comparisons (*e.g.* compond **193** compared to compound **177** and compound **191** compared to compound **160**).

The two other classes of biphenyl, one with an ethyl-linked *trans*-4-pentylcyclohexyl moiety as an 'alkyl chain' and the other with a methoxy-linked *trans*-4-heptylcyclohexyl moiety as an 'alkoxy chain', both represent three ring systems and therefore would be expected to have higher melting points and greater mesophase thermal stabilities than for the straight chain biphenyl systems (compounds **191-195**).

Table 21

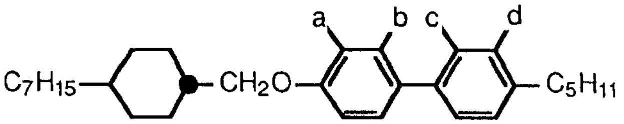
Transition Temperatures (°C) for 2,3-Difluoro-4-(or -4'-)octoxy-4'-(or -4-)(*trans*-4-pentylcyclohexylethyl)biphenyls **(199 and 205)**



Compound			Transition Temperatures (°C)								
No.	a and b	c and d	K		S_C		S_A		N		I
199	H	F	*	59.0	---------------		*	113.5	*	124.0	*
205	F	H	*	32.5	*	55.0	*	83.0	*	122.0	*

Table 22

Transition Temperatures (°C) for 2,3-Difluoro-4'-(or -4-)(*trans*-4-heptylcyclohexylmethoxy)-4-(or -4'-)pentylbiphenyls **(209 and 213)**



Compound			Transition Temperatures (°C)								
No.	a and b	c and d	K		S_B		S_A		N		I
209	H	F	*	54.0	(*	42.0)	*	111.5	*	116.0	*
213	F	H	*	51.0	---------------		*	91.0	*	110.0	*

Although, as for the simple biphenyl systems (**191-195**), each aromatic ring is considered an end ring, the aromatic ring with the cyclohexyl-substituent is obviously different to the aromatic ring containing the straight chain moiety.

Compounds **199**, **205**, **209** and **213** are all very similar in that they are alkyl-alkoxy-substituted *ortho*-difluorobiphenyls and each compound has a cyclohexane ring as part of the alkyl or alkoxy chain. It is, therefore, expected that their melting points would be very similar. However, although compounds **199**, **209** and **213** melt at ~50-60 °C, compound **205** has a usefully low melting point of 32.5 °C. It is most difficult to explain this low melting point but melting points often do not follow any distinct pattern and unexpected values often arise.

The values for mesophase thermal stabilities are as usual more regular. Compounds **199** and **209** have the two fluoro-substituents in the end ring and have greater nematic (by 2.0 and 6.0 °C respectively) and smectic (by 30.5 and 20.5 °C respectively) phase thermal stabilities than their respective isomers with the two fluoro-substituents in the centre ring (compounds **205** and **213** repectively). Such differences are not as great as for the similar terphenyl situation because there is not a true end ring/middle ring structure as there is for the terphenyls.

The methoxy-linked system (**209**) with the two fluoro-substituents in the end ring is sufficiently smectic in character to show a monotropic S_B phase. No such phase is seen for its isomer (**213**) which is as expected since compounds with substituents in the centre ring are always less smectic in character [sub-section 3.2 (c) (i)]. Both these compounds do not show an S_C phase (or any other tilted mesophases) which is disappointing and slightly surprising in view of the generally very strong tendency of *ortho*-difluoro-substituted systems towards the S_C phase.

The dimethylene linked cyclohexyl system (compound **199**) with the two fluorines in the end ring has no ordered smectic phase below the S_A which is beneficial, however, this compound does not show an S_C either. Compound **205** (the two fluorines are in the central ring), however, has the transition temperatures which were hoped for these compounds. The nematic tendency is very similar to the isomeric compound (**199**) and slightly higher than for the two methoxy-linked cyclohexyl systems (**209** and **213**). The S_A phase thermal stability is, as expected, reduced by 30.5 °C when compared to compound **199** but the beneficial feature of compound **205** is the enantiotropic S_C phase of reasonable thermal stability (55.0 °C). It does not seem likely that it is solely the low melting point which is responsible for the appearance of the S_C phase because the melting points for the other three similar compounds are sufficiently low for any reasonable S_C character to be revealed. It could be the S_C tendency of this compound which is responsible for the low melting point. Why this compound should show an S_C phase when the others do not is difficult to explain. It seems likely that both the methoxy-linked and the dimethylene-linked cyclohexyl-substituted moieties do not support the S_C phase very well; however, the latter unit perhaps supports them better. The octoxy group as part of the unsubstituted ring in compound **205** may be aiding the formation of an S_C phase. More work is being carried out in order to find an explanation and this will include the synthesis of further homologues of the compounds already prepared and some dialkoxy-substituted homologues of compounds **209** and **213**.

These cyclohexyl-substituted biphenyl systems can be compared directly with the straight chain biphenyl systems to discern the advantageous effect of the cyclohexyl moiety upon mesophase thermal stability. If compounds **199** and **205** are compared with compounds **191** and **193** repectively then it is clear that mesophase thermal stabilities have been increased far more than melting points (melting points increase by 45.0 and 24.5 °C; T_{N-I} values by 110.5 and 104.0 °C whilst the S_A phase thermal stability of compound **193** has risen by 71.0 °C to 83.0 °C). Compound **195** is an excellent homologue to compare with compound **205** due to their sharing of common liquid crystal phases. The dimethylene-linked cyclohexyl-substituted derivative (**205**) has only a slightly higher melting point (32.5 *vs.* 25.0 °C), however, the S_C, S_A and N phase thermal stabilities have increased by 43.5, 50.0 and 88.0 °C respectively.

The methoxy-linked cyclohexyl-substituted systems (**209** and **213**) can be compared with the straight chain biphenyl analogues (compounds **193** and **191** respectively). Like the above comparisons, much greater increases in mesophase thermal stabilities are seen than for melting points. Melting points have increased by ~40 °C whereas clearing points have risen by ~95 °C.

Summary of Sub-section 3.2 (c) (ii)

The straight chain biphenyls have very low melting points (much lower than for comparable difluoroterphenyls). The cyclohexyl-substituted biphenyl analogues have higher melting points which are similar to the lower melting of the difluoroterphenyls. Remarkably, certain of the straight chain biphenyls show S_C, S_A and N phases, but thermal stabilities are very much lower than those of the difluoroterphenyls. The cyclohexyl-substituted biphenyls do have greatly increased mesophase thermal stabilities but it is only compound **205** which shows an S_C phase.

Although little S_C tendency is shown by the biphenyl systems our collaborators at R.S.R.E. (Malvern) have formulated ferroelectric (S_C*) mixtures incorporating these compounds. What effect they have on viscosity, birefringence and S_C phase thermal stability will be discussed later (p 298).

3.2 (d) Lateral Cyano-substituted Terphenyls

It was previously discussed (p 274) that the lateral groups necessary to bring about negative dielectric anisotropy are usually bulky and lead to high viscosities and reduced mesophase thermal stabilities. However, the monofluoroterphenyls generally have high clearing points so it was hoped that the additional size of a cyano-substituent over the fluoro-substituent would not depress the clearing point to an unacceptable level and perhaps even retain a tendency towards the S_C phase. The actual levels of negative dielectric anisotropy for such systems needed to be evaluated as they may be sufficient to help counter their expected high viscosity values when considering a use in ferroelectric (S_C*) mixtures. For these reasons compounds **216-217**, **219**, **225-227**, **233** and **234** were prepared. Also to achieve even more negative $\Delta\varepsilon$ values compounds with an additional lateral fluoro-substituent (compounds **235**, **242** and **243**) were prepared. This additional fluoro-substituent was expected to provide the more negative $\Delta\varepsilon$ values with no further increase in viscosity values and with no depression in mesophase thermal stabilities.

This interesting set of compounds was hoped to have very negative $\Delta\varepsilon$ values whilst still retaining a tendency towards the S_C phase. If the expected high viscosity values can be tolerated then a possible use could be found in ferroelectric (S_C*) mixtures; if the compounds turned out to be mainly nematic in character then a use in mixtures for ECB devices could perhaps be found.

3.2 (d) (i) Transition Temperatures (°C) for Lateral Cyano-substituted Terphenyls (compounds **216**, **217**, **219** and **225-227**, Table 23, p 293 and compounds **233** and **234**, Table 25, p 295)

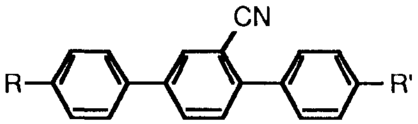
Compounds **216**, **217**, **219** and **225-227** have the lateral cyano-substituent in the centre ring and their transition temperatures can be compared with the appropriate parent system and the appropriate monofluoroterphenyl (preared by Chan).[127-130]

Compounds **216** and **217** have identical terminal chains and although compound **217** is a dialkoxy-substituted compound (which are not usually prepared due to unacceptably high melting points) the melting point is low enough for the S_C phase to be exhibited (albeit monotropically). Compound **216** being dialkyl-substituted is low melting (40.0 °C), the cyano-substituent has therefore caused a depression in the melting point of 152 °C compared to compound **296** and the additional depression in melting point over the monofluoroterphenyl (compound **297**) is 11.5 °C. The alkyl-alkoxy-substituted compounds (**219**, mp 35.5 °C and **226**, mp 48.0 °C) compare with their parent system (compound **97**, mp 205 °C) and the melting point depressions caused by the lateral cyano-substituent are 169.5 and 156.5 °C respectively. Similarly the octoxy homologues **225** and **227** have had their melting points reduced from 194.5 °C (compound **98**) by 161.0 and 159.5 °C to 33.5 and 35.0 °C respectively. When compounds **219** and **225-227** are compared with their appropriate fluoro-substituted compounds (**298-301** respectively) then melting points are seen to be lower for the cyano-substituted systems by 34.5, 35.5, 14.0 and 12.0 °C respectively.

The effect of the large cyano-substituent on mesophase thermal stability is much greater than for the melting points. Compound **216**, despite a low melting point can only

Table 23

Transition Temperatures (°C) for 4-Alkoxy-2'-cyano-4"-pentyl-, 4"-Alkoxy-2'-cyano-4-pentyl-, 2'-Cyano-4,4"-dihexoxy-, and 2'-Cyano-4,4"-dipentyl- terphenyls **(216, 217, 219** and **225-227)**



Compound			Transition Temperatures (°C)								
No.	R	R'	K		S_C		S_A		N		I
216	C_5H_{11}	C_5H_{11}	*	40.0	--------------		(*	33.5	*	38.0)	*
217	$C_6H_{13}O$	$C_6H_{13}O$	*	101.5	(*	61.0)	*	110.0	*	114.0	*
219	$C_6H_{13}O$	C_5H_{11}	*	35.5	--------------		*	97.5	--------------		*
225	$C_8H_{17}O$	C_5H_{11}	*	33.5	--------------		*	103.0	--------------		*
226	C_5H_{11}	$C_6H_{13}O$	*	48.5	(*	29.5)	--------------		*	77.5	*
227	C_5H_{11}	$C_8H_{17}O$	*	35.0	*	42.0	--------------		*	78.0	*

exhibit monotropic mesophases, this equates to a reduction in S_A phase thermal stability of 179.5 °C (compound **296**, $T_{S_A\text{-}N}$ at 213.0 °C). Comparing compound **216** with its fluoro-substituted analogue **(297)** it is seen that the S_B phase has been totally eliminated and the S_A and N phases have been reduced by 76.0 and 98.5 °C respectively. Note that the nematic phase has been reduced more than the smectic phase; this is presumably because the extra dipole of the cyano-substituent upholds the smectic phase thermal stability (such dipole effects do not affect the nematic phase).

An interesting feature revealed by compounds **219** and **225-227** is that when the cyano-substituent is pointing towards the alkoxy-substituent (compounds **226** and **227**) then S_C and N phases are exhibited; however, when it points towards the alkyl-substituent then the compounds (**219** and **225**) are purely S_A in character. For compounds **219** and **225** the S_A phase thermal stabilities of 97.5 and 103.0 °C respectively are lower than the parent systems (compounds **97** and **98**) by 131.0 and 118.5 °C respectively. The additional reduction over the fluoro-substituent (compounds **298** and **299** respectively) are 57.5 and 55.0 °C respectively. Compounds **226** and **227** cannot be compared with their parent systems but S_C/N phase thermal stabilities of 29.5/77.5 and 42.0/78.0 °C respectively represent reductions from the fluoro-substituted analogues (compounds **300** and **301** respectively) of 84.0/85.0 and 74.5/77.0 °C respectively.

Promising results (Table 24, p 294) were obtained when small amounts (5-15 wt%) of compounds **216** were mixed with two of Chan's monofluoroterphenyls (see p 273). It can be seen that the ordered smectic phases are totally eliminated but the S_C, S_A and N phases are only slightly depressed.

Table 24

Transition Temperatures (°C) for Mixtures of Compound 216 in Host Materials

F8O.5T and F9.3T

Composition	K	S_J	S_I	S_C	S_A	N	I
100% **F8O.5T**	* 47.0	(* 40.0	* 53.5	* 116.5	* 130.0	* 155.0	*
95% **F8O.5T** 5% **216**	* 39.0 (18.0)	----------	----------	* 108.5	* 123.0	* 149.0	*
84% **F8O.5T** 16% **216**	* 37.0 (8.0)	----------	----------	* 90.5	* 102.0	* 137.5	*

Composition	K	S_B	S_C	S_A	N	I
100% **F9.3T**	* 46.0	(* 35.0)	* 52.0	* 89.0	* 126.5	*
95% **F9.3T** 5% **216**	* 42.5 (3.0)	------------	* 48.0	* 80.0	* 122.0	*
85% **F9.3T** 15% **216**	* 36.0 (-2.0)	------------	* 39.0	* 60.5	* 113.0	*

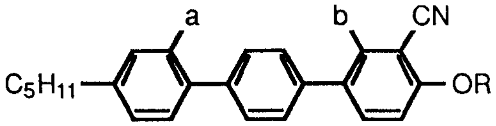
These results are similar to those obtained on mixing the difluoroterphenyl compound (**128**, fluorines inherently fixed either side of the molecule) with the same host materials [sub-Section 3.2 (b) (i), p 272] and were again confirmed by our collaborators at R.S.R.E. (Malvern).

Overall, these lateral cyano-substituted terphenyls have remarkably low melting points and, although much reduced when compared with the fluoro-substituted analogues, their mesophase thermal stabilities are still reasonably high. The type of mesophase exhibited depends on the structure of the compound and the S_C phase is seen in certain compounds.

Two compounds (**233** and **234**) were prepared with the cyano-substituent on the outer edge of the aromatic core pointing towards the alkoxy group in the hope of higher S_C phase thermal stabilities. However, although these compounds melt at a reasonable 62.0 °C they only show an S_A phase (T_{SA-I} values of 163.5 and 160.0 °C). The transition temperatures of these compounds (**233** and **234**) can be compared with the parent systems (compounds **97** and **98** respectively) and reductions in melting points of 143.0 and 132.5 °C respectively are seen; respective T_{SA-I} reductions are 65.0 and 61.5 °C. No melting points were identified for the fluoro-substituted analogues (**102** and **103**, p 265) but respective clearing points are 37.5 and 35.0 °C higher than for these two cyano-substituted compounds. The higher melting points and higher clearing points of compounds **233** and **234** when compared to compounds **219** and **225-227** are expected since the cyano-substituent occupies an outer core position which provides more space giving less

Table 25

Transition Temperatures (°C) for 4-Alkoxy-3-cyano-2-fluoro-4''-pentyl- and 4''-Alkoxy-3''-cyano-2-fluoro-4-pentyl- terphenyls and Parent Systems **(233-235, 242 and 243)**



Compound				Transition Temperatures (°C)				
No.	R	a	b	K		S_A		I
233	C_6H_{13}	H	H	*	62.0	*	163.5	*
234	C_8H_{17}	H	H	*	62.0	*	160.0	*
235	C_8H_{17}	F	H	*	48.0	*	118.0	*
242	C_6H_{13}	H	F	*	100.5	*	167.0	*
243	C_8H_{17}	H	F	*	100.0	*	163.5	*

molecular broadening and no inter-annular twist is possible. This parallels the results seen when discussing the fluoro-substituted analogues (see p 263).

3.2 (d) (ii) Transition Temperatures (°C) for Lateral Cyano-fluoro-substituted Terphenyls (compounds **235**, **242** and **243**, Table 25, p 295)

All three compounds (**235**, **242** and **243**) have the cyano-substituted on the outer edge of the core *ortho* to the alkoxy chain. Where the fluoro-substituent is placed in the same ring (*ortho* to the cyano-substituent, compounds **242** and **243**) then both the lateral substituents are inherently fixed on the same side of the molecule. Hence the fluoro-substituent would not be expected to affect melting points or depress mesophase thermal stabilities significantly. However, the melting points have surprisingly increased by ~40 °C to 100.5 and 100.0 °C respectively. Looked at another way, the cyano-substituent which occupies the outer core position has only caused 17.0 and 31.0 °C increases in melting points when compared with the fluoro-substituted analogues (**107** and **108** respectively). It seems even more remarkable that the additional fluoro-substituent in compounds **242** and **243** has caused the $T_{S_A\text{-}I}$ values to increase (by 3.5 °C in each case) especially since the site of occupation is on the inner core of the molecule. Such increases in mesophase thermal stability have been reported previously[226] but these cases involve the substituent on the edge of the core, and all past evidence (including the work reported in this thesis) indicates that additional lateral substituents within the core always reduce mesophase thermal stability. These observations can be explained in the same terms as for the previously reported cases that is the filling up of empty space. In this case the empty space is created by the large size of the cyano-substituent and even though the additional fluoro-substituent is placed inside the core mesophase thermal stabilities are slightly increased. Compounds **107** and **108** do not show an S_A phase, therefore comparison with compounds **242** and **243** respectively is not possible. It is worth noting, however, that the additional cyano-substituent has removed the S_C and nematic phases to give compounds with a pure S_A phase.

When the fluoro-substituent is placed in a different ring to the cyano-substituent (compound **235**) the two groups are not fixed on one side of the molecule and the net breadth of the molecule is therefore increased. Accordingly the melting point is quite low (48.0 °C) and represents a reduction of 14.0 °C when compared to compound **234**; the $T_{SA\text{-}I}$ value has also been reduced by 42.0 °C to 118.0 °C. When compared to compound **112** (fluoro-substituted analogue) the cyano-substituent has reduced the melting point by 54.0 °C from 102.0 °C and again the S_C and N phases of compound **112** have been replaced by the S_A phase.

3.2 (e) Lateral Trifluoromethyl-substituted Terphenyls

In order to determine the effect of a lateral trifluoromethyl group on dielectric anisotropy, viscosity and mesophase transition temperatures a terphenyl system has been used. The one compound reported can be compared with the analogous fluoro- and cyano-substituted systems in order to discern its suitability for ferroelectric mixture use. As for the cyano-substituted system the lateral group is large and therefore a high viscosity was expected to combine with low mesophase tendency.

3.2 (e) (i) Transition Temperatures (°C) for Lateral Trifluoromethyl-substituted Terphenyls (compound **248**)

Only one compound (**248**) of this type was prepared [transitions (°C) K 32.0 (S_C 9.0) I]. The melting point is low (32.0 °C) (as has now become expected of certain lateral substituted systems) and is 16.5 °C lower than for the cyano-substituted analogue (**226**) and 30.5 °C lower than for the fluoro-substituted system (**300**). The large trifluoromethyl-substituent has caused a large reduction (173.0 °C) in melting point from the parent system (**97**) and the mesophase thermal stability has been drastically affected (clearing point has been reduced by 219.5 °C) and no enantiotropic mesophase is exhibited. The most surprising feature of this compound (**248**) is the appearance of a lone S_C phase ($T_{SC\text{-}I}$ value of 9.0 °C). The thermal stability of the S_C phase is 20.5 °C lower than for the cyano analogue (**226**) and 104.5 °C lower than the fluoro analogue (**300**).

Although an S_C Phase is seen in compound **248** the trifluoromethyl-substituent greatly reduces the mesophase thermal stability and this combined with the high viscosity (480 cP measured as a 10 wt% solution in the I compound eutectic mixture at 30 °C) make this type of compound of no use in ferroelectric mixtures. No further physical property results are available.

3.2 (f) Physical Properties of Lateral *ortho*-Difluoro-substituted Terphenyls (compounds **147-149**, **159**, **160**, **175**, **179**) and Biphenyls (compounds **195**, **205**)

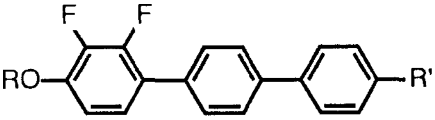
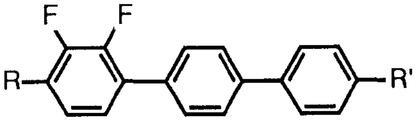
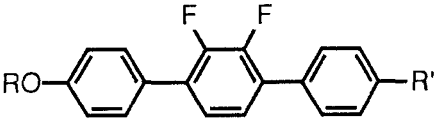
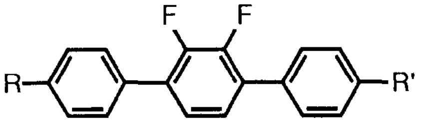
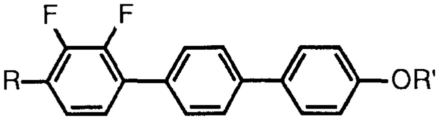
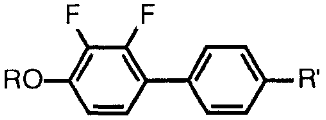
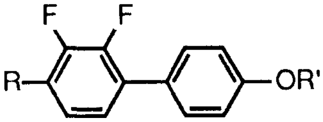
It is clearly seen from Table 26 (p 299) that compound types which have the most negative dielectric anisotropies are those which incorporate the difluoro moiety in an alkoxy-substituted ring (types **A** and **F**). This is due to the push-pull effect; *i.e.*, the alkoxy group feeds electron density into the ring and the *ortho*-fluorine pulls the electron charge from the ring. This arrangement of the two fluoro-substituents at the end of the molecule leads to a high viscosity, which, in terms of display device response time, will counter the high $-\Delta\varepsilon$ value. Compounds of type **E** (which have similar transition temperatures to compounds of type **A**) have the immediate disadvantage of high viscosity without the benefit of high $-\Delta\varepsilon$ values, hence, compounds of this type (**E**) have not been used in the ferroelectric ($S_C{}^*$) mixtures to be discussed later. This point is quite interesting because it highlights the need for a compound to have good all-round properties. Compounds of type **E** have very large S_C ranges but this alone is not good enough for use in ferroelectric ($S_C{}^*$) mixtures when better compounds (type **A**) are available. The compounds of type **B** (dialkyl), however, do have the advantage of high S_C phase thermal stability and lower viscosity. The compounds with the two fluoro-substituents in the centre ring (types **C** and **D**) do have low viscosities and those of type **C** (alkoxy, alkyl) exhibit the S_C mesophase but they also have higher viscosities than compounds of type **D** (dialkyl).

Quite apart fom a large S_C range, the mixtures to be discussed reflect the need for a low viscositiy and a high negative dielectric anisotropy ($-\Delta\varepsilon$).

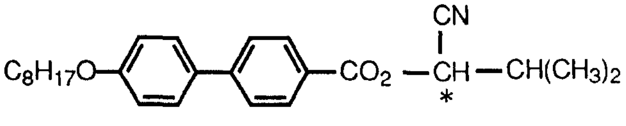
Apart from Table 26 (p 299) which shows the dielectric anisotropy of the different

Table 26

Dielectric Anisotropy and Viscosity Results for *ortho*-Difluoro-substituted Terphenyls and Biphenyls

Compound	Dielectric Anisotropy (Δε)	Viscosity (cP)
 **(A)**	-4.2	130
 **(B)**	-2.0	80
 **(C)**	-2.1	60
 **(D)**	-2.0	35
 **(E)**	-2.1	130
 **(F)**	-4.7	57
 **(G)**	-2.6	80

structural modifications of the *ortho*-difluoro-substituted terphenyls and biphenyls, all the physical property results from our collaborators at R.S.R.E. (Malvern) centre around their ferroelectric (S_C*) mixtures which have been prepared using the various *ortho*-difluoro-substituted terphenyls and biphenyls as host materials, and a transverse chiral cyano dopant [compound XXVIII (chiral dopant **I**)] which was first synthesised by



(XXVIII)

K 67.0 I

Dr I.G. Shenouda.[126]

This dopant was found to be ideal because it induces an S_A phase into the host mixtures which do not have an S_A phase, it induces a large P_S and gives ferroelectric mixtures with a long 'nematic' pitch.

ortho-Difluoroterphenyl-based ferroelectric (S_C*) mixtures to be discussed are based on two eutectic non-chiral mixtures [far more were tested and more work is being carried out in this area by our collaborators at R.S.R.E. (Malvern)]; their constitution is shown below (Table 27, p 300).

Host mixture **1** is a eutectic mixture based on alkyl-alkoxy-substituted *ortho*-difluoroterphenyls including the higher melting, high T_{SC-X} transition compounds **147** and **148**) which have very high negative Δε values *i.e.* type **A** compounds (also of high viscosity). Lower melting, lower T_{SC-X} value compounds (**159** and **160**) are added in smaller amounts to reduce the melting point and S_C phase thermal stability for the mixture. This mixture (**1**) does not have an S_A phase but, as will be shown later, the

Table 27

The Composition of Two Non-chiral Host Mixtures Based on *ortho*-Difluoroterphenyls

Host Mixture **1**

Compound **147** (6OFF5T)	37.3%
Compound **148** (8OFF5T)	40.8%
Compound **159** (FF6O5T)	13.6%
Compound **160** (FF8O5T)	8.3%

Transition Temperatures (°C) K 24.0 S_C 97.0 N 146.0 I

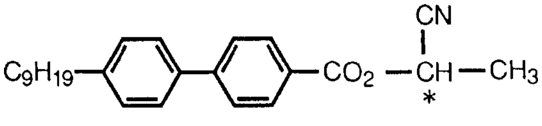
Host Mixture **2**

Compound **179** (FF75T)	33.3%
Compound **175** (FF55T)	33.3%
Compound **149** (5FF5T)	33.3%

Transition Temperatures (°C) K 15.5 S_C 91.5 S_A 97.0 N 127.0 I addition of the chiral dopant **I** induces an S_A phase into the ferroelectric (S_C*) mixture (important for molecular alignment).

Host mixture **2** is a eutectic mixture based on the dialkyl-substituted *ortho*-difluoroterphenyls. Equal amounts of three compounds are used; compounds **179** and **175** are of moderate melting point and have quite high S_C phase thermal stabilities. Of special interest is the use of compound **149** (5FF5T) which is not particularly low melting (60.0 °C) and does not have an S_C phase (purely nematogenic), however, in this mixture (and others not discussed here) it has the ability to hold up the S_C phase thermal stability to a much greater degree than would be expected (*i.e.* S_C phase thermal stability much higher than the 60.0 °C melting point). Compounds **150**, **151** and **152** all appear to be better as they have lower melting points and do show an S_C phase, however, our collaborators at R.S.R.E. (Malvern) report that they are more than satisfied with the use of compound **149** (5FF5T) which has a lower viscosity than the longer alkyl chain derivatives.

Mixture **2** has the advantage of much lower viscosity than host mixture **1** since it is based on dialkyl-substituted systems, however, it has the disadvantage of less negative dielectric anisotropy (-1.9 vs. -2.7). It will be revealed later how this affects the response time when the mixtures are applied to a ferroelectric display device. A chiral dopant is required to enable the achiral host mixtures to be used in a ferroelectric display device. In most cases chiral dopant **I** is used, however, in one ferroelectric mixture a different chiral dopant is used (**II**) in addition to **I**.



Chiral Dopant **II**

K 55.0 I

Besides inducing chirality to the whole mixture, both these chiral dopants induce the P_S into the system which increases as the percentage of chiral dopant increases. Racemic or chiral dopant has the effect of lowering the nematic and S_C phase thermal stabilities and rising the S_A phase thermal stability. Therefore, by varying the percentage of chiral dopant but leaving the total percentage of dopant constant (by using racemic

Table 28

The Composition of Five Ferroelectric Mixtures Based on Host Mixture **1** and Incorporating Chiral Dopants **I** and **II**

Ferroelectric Mixture **A**

Host Mixture **1**	90.0%	P_S	3.3 nC cm^{-2}
Chiral Dopant **I**	1.0%	θ	23.5°
Racemic Dopant **I**	9.0%	$\tau(10\ \mathrm{V}\ \mu\mathrm{m}^{-1})$	180 μs

Transitions (°C) S_C 90.5 S_A 109.5 N 133.0 I

Ferroelectric Mixture **B**

Host Mixture **1**	90.0%	P_S	9.0 nC cm^{-2}
Chiral Dopant **I**	2.5%	θ	23.5°
Racemic Dopant **I**	7.5%	τ	-

Transitions (°C) As for Mixture **A**

Ferroelectric Mixture **C**

Host Mixture **1**	90.0%	P_S	21.0 nC cm^{-2}
Chiral Dopant **I**	7.5%	θ	21.0°
Racemic Dopant **I**	2.5%	$\tau(10\ \mathrm{V}\ \mu\mathrm{m}^{-1})$	25 μs

Transitions (°C) As for Mixture **A**

Ferroelectric Mixture **D**

Host Mixture **1**	90.0%	P_S	38.0 nC cm^{-2}
Chiral Dopant **I**	10.0%	θ	27.0°
Transitions (°C) As for Mixture **A**		$\tau(10\ \mathrm{V}\ \mu\mathrm{m}^{-1})$	9 μs

Ferroelectric Mixture **E**

Host Mixture **1**	80.0%	P_S	39.0 nC cm^{-2}
Chiral Dopant **I**	7.6%	θ	18.5°
Chiral Dopant **II**	12.4%	$\tau(10\ \mathrm{V}\ \mu\mathrm{m}^{-1})$	3 μs

Transitions (°C) S_C 63.0 S_A 115.0 N 124.0 I

dopant) the transition temperatures will be constant but the P_S value will vary; this enables response times to be measured as a function of P_S. It is important for comparison to maintain a similar T_{SC-SA} value (~60 °C in most cases) as response times are measured at a certain temperature (30 °C) which is so much into the S_C phase; if the T_{SA-SC} value is higher (~90 °C) then 30 °C is deeper into the S_C phase and therefore not comparable.

The constitution of some ferroelectric (S_C*) mixtures prepared by R.S.R.E. (Malvern) and their physical properties are shown in Table 28 (p 302).

It can be seen from Table 28 that in going from ferroelectric mixture **A** through to **D** the total amount of dopant is constant and so the transition temperatures remain constant. However, as the amount of chiral dopant increases from 1.0% to a full 10% in going from **A** to **D** the P_S rises from 3.3 to 38.0 nC cm^{-2} and consequently this reduces the response time. The T_{SC-SA} transition is too high (90.5 °C) for these alkoxy-alkyl-substituted mixtures to compare with the dialkyl-substituted mixtures (**F-H**). In order to bring the T_{SC-SA} value down to ~60 °C chiral dopant **II** was used in addition to chiral dopant **I** and this gave ferroelectric mixture **E**. The twist sense of chiral dopant **II** is opposite to that of chiral dopant **I** and a total chiral dopant of 20% is used to give a P_S value of 39.0 nC cm^{-2}.

The series of dialkyl-substituted terphenyl based ferroelectric mixtures **F-H** (Table 29, p 304) show reduced P_S values compared to equivalent alkoxy-alkyl-substituted terphenyl based mixtures **A-E**. Mixture **F** has just 2.5% total dopant added which is all chiral and this gives a similar P_S value to mixture **F** (also 2.5% chiral dopant, but also 7.5% racemic dopant). However, the increased total dopant for mixture **G** increases the S_A phase thermal stability but reduces the S_C and nematic phase thermal stabilities and because the measurements are taken at 30 °C then this is further into the S_C phase for mixture **F** and therefore the tilt angle is slightly greater. Mixture **G** compares with mixture **B** in that they have the same dopant quantities, however, the T_{SC-SA} value is much higher for mixture **B** and so true comparison is impossible.

As mentioned previously, mixture **E** was specially formulated to give a T_{SC-SA} value of ~60 °C in order to compare with mixture **H**; it is these two mixtures which are the most important and will be discussed in more detail. In order to obtain fast-switching ferroelectric (S_C*) mixtures the P_S needs to be high, the dielectric anisotropy ($\Delta\varepsilon$) must be highly negative and the viscosity must be low. Mixtures **E** and **H** are the fastest switching

Table 29

The Composition of Three Ferroelectric Mixtures Based on Host Mixture **2** and Incorporating Chiral Dopant **I**

Ferroelectric Mixture **F**			
Host Mixture **2**	97.5%	P_S	7.0 nC cm^{-2}
Chiral Dopant **I**	2.5%	θ	23.0°
Transitions (°C) S_C 87.0 S_A 102.0 N 125.0 I		τ(10 V μm^{-1})	-
Ferroelectric Mixture **G**			
Host Mixture **2**	90.0%	P_S	7.2 nC cm^{-2}
Chiral Dopant **I**	2.5%	θ	21.5°
Racemic Dopant **I**	7.5%	τ(10 V μm^{-1})	7 μs
Transitions (°C) S_C 60.0 S_A 105.5 N 116.0 I			
Ferroelectric Mixture **H**			
Host Mixture **2**	90.0%	P_S	30.0 nC cm^{-2}
Chiral Dopant **I**	10.0%	θ	21.5°
Transitions (°C) As for Mixture **G**		τ(10 V μm^{-1})	3 μs

ferroelectric mixtures available at the present time and they achieve these fast times in different ways. Mixture **E** has a slightly higher P_S and a much more negative $\Delta\varepsilon$ value, yet the switching speeds are identical [3 μs (10 V μm^{-1})]; this is because mixture **H** has a much lower viscosity. This lower viscosity, the use of just 10% of a single chiral dopant (chiral dopant **I**) and the lower crystal tendency make mixture **H** the more attractive.

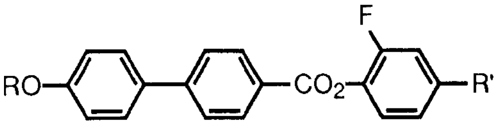
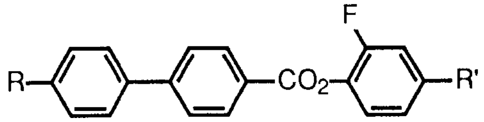
Until now the best host materials for ferroelectric mixtures have been the MBF esters[131] (compounds XXX and XXXI in Table 30, p 305).

It can be seen by comparing the values in Table 30 with those in Table 26 (p 299) that the MBF esters have much less negative $\Delta\varepsilon$ values and much higher viscosity values than the *ortho*-difluoro-substituted terphenyls.

Table 30 also shows the fastest ferroelectric mixture based on MBF esters and it can be seen that the switching speed is six times slower than for the directly comparable mixtures based on the *ortho*-difluoro-substituted terphenyls (**E** and **H**). It is not just

Table 30

The Dielectric Anisotropy and Viscosity Values for Alkyl- and Alkoxy-Substituted MBF Esters and Some Physical Property Measurements of a Ferroelectric Mixture

Compound	Dielectric Anisotropy ($\Delta\varepsilon$)	Viscosity (cP)
 XXX	-1.3	540
 XXXI	-0.8	270

Ferroelectric Mixture **J** (based on MBF esters)

Transitions (°C) S_C 68.0 S_A 98.0 N 130.0 I

P_S	29.0 nC cm^{-2}
θ	19.0°
τ(10 V μm^{-1})	18 μs

switching speeds which makes a good ferroelectric mixture as other factors need to be satisfied, such as good alignment, ability to fill the cells (low clearing point), easily multiplex-driven and compound stability. This is also where the difluoroterphenyl-based mixtures are seen to be excellent host materials. Birefringence values ($\Delta n = 0.19$) may appear to be high (the birefringence of the MBF esters is also high, $\Delta n = 0.18$) but the trend towards thinner cells makes birefringence less important. However, the ideal optical path difference for the ferroelectric device is ~0.28 μm which is achieved for this birefringence by using 1.5 μm thick cells (see Introduction, p 46).

It can be concluded that *ortho*-difluoro-substituted terphenyls are excellent host materials for ferroelectric mixtures. Eutectic mixtures have melting points below room temperature with broad S_C ranges and small S_A and nematic phases for good alignment. They are of low viscosity with high negative $\Delta\varepsilon$ values and in conjunction with chiral dopant **I** give high P_S mixtures which have the fastest response times known (as little as 1 μs at 30 °C).

The *ortho*-difluoro-susbtituted biphenyls (**191-195**) were prepared as lower melting, lower viscosity, lower birefringence additives for the analogous terphenyl-based systems. Compound **193** (FF580B) was used in 20 wt% in host mixtures **1** and **2**; with 2.5% active and 7.5% racemic dopant **I** in the case of host mixture **1** (ferroelectric mixture **K**). In the case of host mixture **2** only 2.5% active dopant **I** was used in order to prevent the T_{SC-SA} transition from falling too low. The results are shown in Table 31.

Table 31

The Composition of Two Ferroelectric Mixtures Incorporating Compound **193** and Chiral Dopant **I**

Ferroelectric Mixture **K**

Host Mixture **1**	70.0%	P_S	5.7 nC cm^{-1}
Compound **193** (FF58OB)	20.0%	θ	20°
Chiral dopant **I**	2.5%	τ(10 V μm^{-1})	32 μs
Racemic Dopant **I**	7.5%		

Transitions (°C) S_C 62.5 S_A 84.5 N 107.5 I

Ferroelectric Mixture **L**

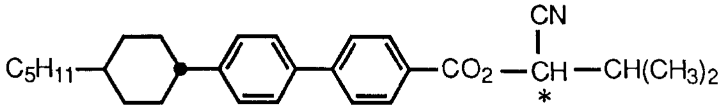
Host Mixture **2**	77.5%	P_S	6.8 nC cm^{-2}
Compound **193** (FF58OB)	20.0%	θ	23.5°
Chiral Dopant **I**	2.5%	τ(10 V μm^{-1})	10 μs

Transitions (°C) S_C 59.0 S_A 75.5 N 97.0 I

The inclusion of the biphenyl compounds into the terphenyl-based mixtures has not reduced the birefringence or the viscosity of the resultant ferroelectric mixtures to any significant degree. The response times are fast but not as good as for those mixtures without the biphenyls, there is the benefit of lower melting points but the disadvantage of the S_C phase thermal stability being significantly reduced.

The incorporation of a cyclohexyl moiety into the *ortho*-difluoro-substituted biphenyls (compounds **199, 205, 209** and **213**) was intended to increase the liquid crystal phase thermal stability (particularly S_C) and give lower birefringence and lower viscosity values. The anticipated higher S_C phase thermal stability would enable larger percentages to be included in terphenyl-based mixtures to give ferroelectric mixtures with lower birefringence and lower viscosity without significantly reducing the $T_{SC\text{-}SA}$ transition. Compounds **199**, **209** and **213** have quite low melting points and as expected have high liquid crystal phase thermal stabilities but they do not show an S_C phase. Compound **205**, however, does show an S_C phase and has a low viscosity (88 cP) so this compound was investigated further by our collaborators at R.S.R.E. (Malvern).

A ferroelectric mixture (**M**) was prepared using compound **205** as the sole S_C host material and 2.5% of a chiral dopant (**III**).



Chiral Dopant **III**

K 89.0 (S_B 74.0 S_A 75.0) I

Table 32

The Composition of a Ferroelectric Mixture Incorporating Compound **205** and Chiral Dopant **III**

Ferroelectric Mixture **M**

Compound **205**	97.5%	P_S	1.8 nC cm^{-2}
Chiral Dopant **III**	2.5%	θ	14°

Transitions (°C) S_C 38.5 S_A 81.0 N 114.0 I

The birefringence of mixture **M** is 0.13 which is significantly lower than for the ferroelectric mixtures based on the difluoroterphenyl host mixtures ($\Delta n = 0.19$). The response times for ferroelectric mixture **M** are similar to those of the difluoroterphenyl-based mixtures and are around four times faster than mixtures based on MBF esters.

When compound **205** is mixed with host mixture **2** (p 300) the S_C and S_A phase thermal stabilities are depressed as shown in Table 33 (p 308).

These results clearly indicate that the S_C and S_A phases of compound **205** are not compatible with those of the *ortho*-difluoroterphenyl host mixture **2**. The addition of a chiral dopant to the above mixtures would reduce the S_C phase thermal stability even further thus making such ferroelectric mixtures impractical.

Table 33

The Incompatability of the Smectic A and C Phases of Compound **205** with those of Host Mixture **2**

% Compound **205**	% Host Mixture **2**	S_C		S_A		N		I
0	100	*	91.5	*	97.0	*	127.0	*
33	67	*	51.0	-------------		*	121.0	*
50	50	*	38.0	-------------		*	119.0	*
67	33	*	29.0	-------------		*	117.0	*
100	0	*	55.0	*	83.0	*	122.0	*

Ferroelectric mixture **M** looks promising and therefore work is to be continued in this area in order to perhaps realise a ferroelectric mixture based wholly on the cyclohexyl containing systems with a compatible S_C phase of higher thermal stability.

3.2 (g) Physical Properties of Lateral Cyano- and Cyano-fluoro- substituted Terphenyls (compounds **216**, **225**, **227**, **234**, **243**)

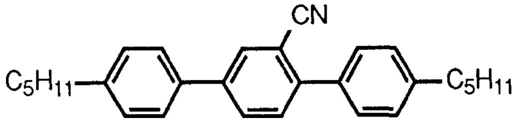
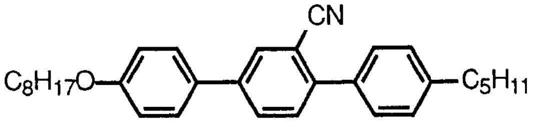
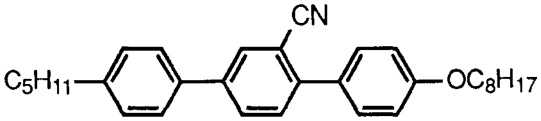
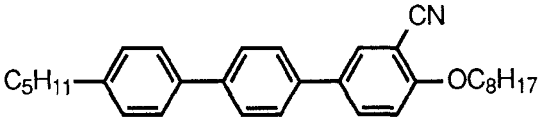
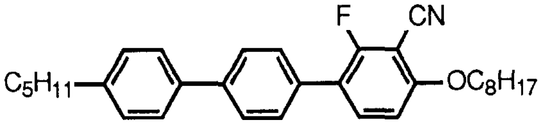
The dielectric anisotropy and viscosity of this type of compound are shown in Table 34 (p 309).

The dielectric anisotropy values of the lateral cyano-substituted terphenyls are very negative (compound **243** has an exceptionally large negative value) which is beneficial for a ferroelectric mixture. However, the viscosity values are extremely large which, despite large negative dielectric anisotropy values, means these compounds will be of no use in ferroelectric mixtures. Viscosity values are larger when the cyano-substituent is positioned on the outer edge of the aromatic core, which is the same as the trend seen for the *ortho*-difluoro-substituted terphenyls [sub-section 3.2 (f)]. Also the dielectric anisotropy is more negative when the cyano-substituent is *ortho* to an alkoxy group, this is due to the effect of the alkoxy group pushing electrons towards the cyano-substituent which is pulling them towards itself (the 'push-pull' effect). The fluoro-substituent of compound **243** has caused a lower viscosity than for compound **234** by filling up space and creating a smoothing effect. Compound **234** has a similar $\Delta\varepsilon$ value to compound type **A** (Table 26, p 299) which indicates that in terms of $\Delta\varepsilon$ values two *ortho*-difluoro-substituents have a similar effect to a cyano substituent but the cyano-substituent causes a much larger viscosity.

Table 34

Dielectric Anisotropy and Viscosity Results for selected

Lateral Cyano-substituted Terphenyls

Compound	Dielectric Anisotropy ($\Delta\varepsilon$)	Viscosity (cP)
 **216**	-	1350
 **225**	-1.6	-
 **227**	-2.9	-
 **234**	-4.7	10000
 **243**	-9.5	5000

3.3 2,6-Disubstituted Naphthalenes

The compounds covered by this section were intended to be nematic materials of high optical anisotropy (Δn). Our collaborators at R.S.R.E. (Malvern) are working on a new technological application for high optical anisotropy (birefringence), highly polarisable materials with, ideally, low melting points and T_{N-I} values at or just above room temperature. Briefly, the application involves the orientational switching of molecules by the use of a laser (as opposed to the electric field switching seen in display devices). The compounds prepared were, therefore, all based on the 2,6-disubstituted naphthalene moiety because it is a compact, conjugated unit, and expected to provide a high birefringence. Since this moiety is quite broad the length was required to be extended in order to obtain nematic materials. This involved the use of a 1,4-phenyl unit which in most cases was linked to the naphthyl moiety by an ethynyl linkage giving highly conjugated systems, with terminal groups which are conducive to high birefringence and providing nematic mesophases (*e.g.* cyano, alkoxy, alk-1-ynyl and alkyl). Inevitably, with the inclusion of these highly polarisable functional groups, melting points were expected to be high but this preliminary work was primarily concerned with gaining some idea about which groups and combinations of groups gave the highest birefringence values.

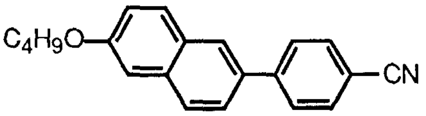
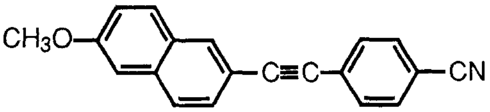
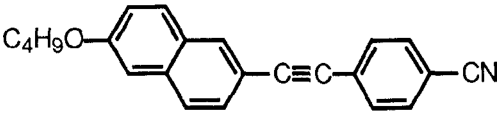
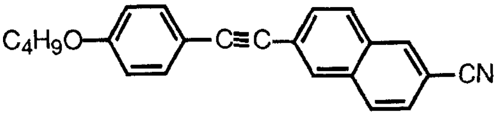
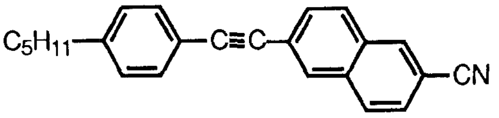
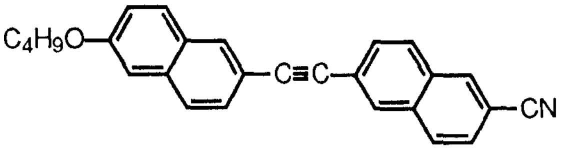
3.3 (a) Transition Temperatures (°C) for Terminal Cyano- and alkoxy- or alkyl- substituted 1,4-phenyl- and 2,6-naphthyl- ethynes (compounds **254**, **259**, **260** and **279-281**, Table 35, p 311)

The 2,6-disubstituted naphthalene system was shown by Gray and Jones[228,229] (1954) to be conducive to liquid crystal phase formation for the series of 6-alkoxy-2-naphthoic acids. 2,6-Disubstituted naphthalene compounds with a terminal cyano-substituent were reported by Coates and Gray[179] (1976). These were alkyl- and alkoxy- substituted 2,6-naphthyl and 1,4-phenyl systems linked by an ester group.

In 1981 Zollinger *et al.*[177] reported on the synthesis of 2-alkoxy-6-(4-cyanophenyl)naphthalenes (including compound **254** with identical transition temperatures). In 1983 Gray and Lacey[230] and Zollinger *et al.*[211] independently reported on 2-alkyl-6-(4-cyanophenyl)naphthalenes which are alkyl homologues of compound **254**.

Table 35

Transition Temperatures (°C) for Terminal Cyano- and alkoxy- or alkyl- substituted 1,4-phenyl- and 2,6-naphthyl- ethynes (**254**, **259**, **260** and **279-281**)

Compound	Transition Temperatures (°C)
 **254**	K 125.0 N 159.0 I
 **259**	K 144.0 N 210.0 I
 **260**	K 106.5 N 186.0 I 111.5
 **279**	K 110.5 N 195.5 I 120.5
 **280**	K 79.5 N 164.0 I
 **281**	K 185.0 N 270.5 I

Comparing the ethyne linked alkoxy-substituted compounds (**260** and **279**) with the similar ester linked compounds of Coates and Gray[179] (no direct homologue comparison is available) it is seen that melting points are ~10 °C higher and the T_{N-I} values are ~35 °C higher for the ethyne linked systems. The pentyl homologue (**280**) is directly comparable to an ester linked system and in this case the ethyne linked compound melts 17.0 °C lower and has a higher T_{N-I} value by just 9.5 °C than its ester linked analogue.

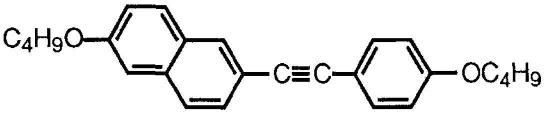
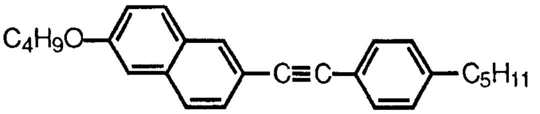
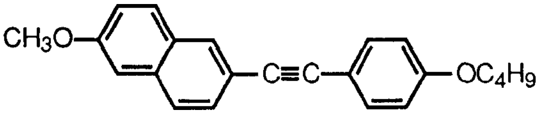
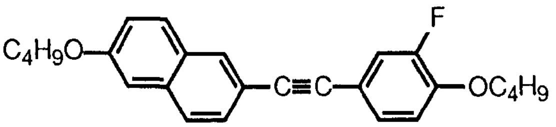
Generally the inclusion of an ethyne linkage within a molecule leads to a significantly higher melting point, but comparing compound **254** (mp 125.0 °C) with compound **260** the melting point is actually reduced by 13.5 °C to 111.5 °C. However, the ethyne linkage is responsible for increasing the T_{N-I} value by 27.0 °C from 159.0 °C (compound **254**) to 186.0 °C (compound **260**). It is interesting that when the cyano-substituent is part of the naphthyl moiety (compound **279**, T_{N-I} value 195.5 °C) then the T_{N-I} value is higher by 9.5 °C than the isomer with the cyano-substituent as part of the phenyl ring (compound **260**, T_{N-I} value 186.0 °C). This can probably be explained by the high polarisability of the cyano- and the naphthyl- substituents being in combination (similar results were shown by Coates and Gray[179]). For perhaps the same reason, the highest melting crystal form of compound **279** is higher by 9.0 °C than that of compound **260**. It is worth mentioning the melting behaviour of compounds **260** and **279** which initially melted to the nematic mesophase at 106.5 and 110.5 °C respectively. In both cases, on further slow heating the compounds crystallised and on further heating melted again to the nematic mesophase at 111.5 and 120.5 °C respectively. This indicates that for both compounds the higher melting crystal form is stable at a temperature within the nematic range. This behaviour is not revealed when a fast rate of heating is used because the crystals have no time to form before the sample is above the higher melting point, or by DSC analysis for the same reason. The methoxy homologue of compound **260** (compound **259**) was prepared for increased birefringence and as expected has a much higher melting point (by 32.5 °C) and a higher clearing point (by 24.0 °C). Again to provide compounds of increased birefringence, compound **281** was prepared; the use of two naphthyl-substituents has led to a very high T_{N-I} value, however, the melting point is also very high. This substitution of a further 2,6-naphthyl-substituent in place of the 1,4-phenyl moiety in compounds **260** and **279** has caused increased melting points of 73.5 and 64.5 °C respectively and the T_{N-I} values have increased by 84.5 and 75.0 °C respectively in going to compound **281**.

3.3 (b) Transition Temperatures (°C) for Terminal Alkoxy- and Alkyl- substituted 1,4-phenyl- and 2,6-naphthyl- ethynes (compounds **267-269** and **274**, Table 36, p 313)

High melting points were a feature of the cyano-substituted systems just discussed and so to determine if suitably high birefringent materials of lower melting point can be achieved by the use of alkyl and alkoxy groups a selection of compounds were prepared. Dialkoxy-substituted compounds were prepared in this section in an attempt to obtain high birefringent materials despite the expected high melting points.

Table 36

Transition Temperatures (°C) for Terminal Alkoxy- and Alkyl- substituted 1,4-phenyl- and 2,6-naphthyl- ethynes (**267-269** and **274**)

Compound	Transition Temperatures (°C)
 **267**	K 149.0 N 178.5 I
 **268**	K 82.0 N 143.0 I
 **269**	K 131.0 N 185.0 I
 **274**	K 132.0 N 153.0 I

Compound **267** has a very high melting point (149.0 °C) which is not unexpected since both terminal substituents are alkoxy and equivalent. The fall in melting point on substituting one alkoxy-substituent for an alkyl-substituent (compound **268**) is very pleasing (67.0 °C) since the $T_{N\text{-}I}$ value is still very high at 143.0 °C (a fall of 35.5 °C, which is a typical difference between alkoxy- and alkyl- substituents). The dialkoxy-substituted compound (**269**) with different terminal substituents gives a lower melting point than compound **267** but still melts very high at 131.0 °C and the effect of the methoxy-substituent has increased the T_{N-I} value by 6.5 °C to 185.0 °C.

Lateral fluoro-substitution is now a well recognised[33] way to lower melting points; the T_{N-I} value is usually lowered by a similar degree but this is not important when T_{N-I} values are very high for the parent systems. In view of the high melting point of compound **267**, a fluoro-substituted analogue was prepared. The decrease in melting point (17.0 °C) was not as much as was hoped for and the decrease in the T_{N-I} value of 25.5 °C was also less than might be expected. However, this is due to the fluoro-substituent being on the edge of the core. Indeed a greater reduction in melting point may have been achieved with the fluoro-substituent *ortho* to the ethyne linking group, however the presence of a linking group prevents the fluoro-substituent causing any inter-annular twists and also provides space. This means that the effects of fluoro-substituents on biphenyl[164] and terphenyl[127-130,164] systems (*i.e.* broadening of the molecule and inter-annular twist induction) cannot be fully realised in these ethyne linked compounds (and probably with other linking groups for example -C_2H_4- and -CH_2O-).

To determine the effect of replacing a cyano-substituent with an alkyl- or alkoxy-substituent several comparisons can be made. Where a butoxy-substituent has replaced the cyano-substituent in compound **269** the melting point has fallen by 13.0 °C and the T_{N-I} value by 25.0 °C compared with compound **259**. The same comparison of compounds **268** and **280** gives a higher melting point by 2.5 °C but the clearing point has been reduced by 21.5 °C. If compounds **267** and **260** are compared it is seen that the melting point has risen by 37.5 °C because compound **267** now has equivalent terminal substituents and the T_{N-I} value has fallen by 7.5 °C. Compound **267** can also be compared with compound **279** here the cyano-substituted compound (**279**) has a lower melting point by 28.5 °C and a higher T_{N-I} value by 17.0 °C. The comparisons show that substituting a terminal cyano-substituent for an alkoxy-substituent has little effect on melting point, often causing an increase, yet T_{N-I} values are reduced by variable degrees (7.5-25.0 °C). The replacement of the cyano-substituent in compound **260** (mp 111.5 °C) with a pentyl-substituent (compound **268**, mp 82.0 °C) produced a very useful reduction in melting point of 29.5 °C; the clearing point has fallen by 43.0 °C but is still very high at 143.0 °C. This type of substitution, however, is bound to reduce the birefringence considerably.

3.3 (c) Transition Temperatures (°C) for Terminal Alkoxy-, Alkyl- and Alk-1-ynyl-substituted 1,4-phenyl- and 2,6-naphthyl- ethynes, a Lateral Fluoro-substituted Derivative and a Terminal Bromo-substituted Derivative (compounds **271**, **272**, **283**, **287** and **288**, Table 37, p 316)

With the exception of compound **273** (a terminal bromo-substituted compound) all compounds in Table 37 (p 316) have a terminal pent-1-ynyl-substituent. This substituent was used to increase conjugation of the system and therefore increase the birefringence; whilst hopefully retaining the lower melting characteristics of the alkyl chain.

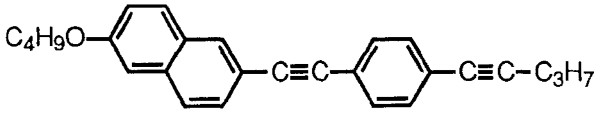
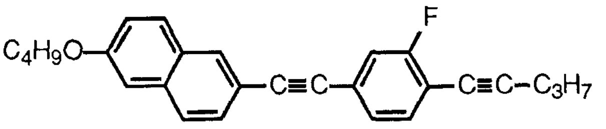
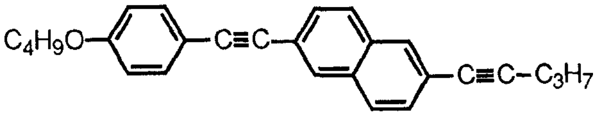
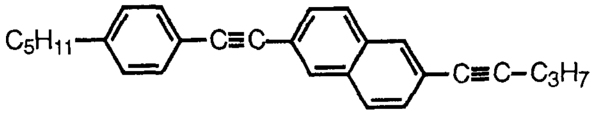
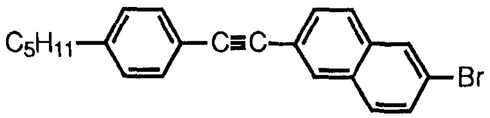
Compound **271** (mp 126.5 °C) can be compared with compound **267** (mp 149.0 °C) and the use of the pent-1-ynyl-substituent has reduced melting point by 22.5 °C which is what was hoped for, however, the melting point is still very high at 126.5 °C which is disappointing. The pent-1-ynyl-substituent does have the ability to support high T_{N-I} values which is substantiated by comparing compound **271** with compound **267** where the T_{N-I} value is only 7.5 °C lower for compound **271**. To discern the effect of replacing a pentyl-substituent with a pent-1-ynyl-substituent compound **268** can be compared with compound **271**. Disappointingly the pent-1-ynyl-substituent causes a higher melting point by 44.5 °C but the T_{N-I} value increases by 28.0 °C. The use of a lateral fluoro-substituent in compound **272** was an attempt to lower the melting point, which has been achieved (by 24.0 °C). However, as is often the case smectic phases are supported by a lateral fluoro-substituent placed on the edge of the core[33,226] and an S_A phase has been induced and the T_{N-I} value has fallen by 27.0 °C when compared to compound **271**. Comparing compound **272** with the other fluoro-substituted compound (**274**) shows the expected lower melting point of compound **272** (by 29.5 °C) and that the lower melting point enables an SA phase to be seen; the T_{N-I} value of compound **272** is again only reduced by

9.0 °C.

It is found therefore that the pent-1-ynyl-substituent gives compounds with melting points which are intermediate between those of butoxy-substituted analogues and those of pentyl-substituted compounds. T_{N-I} values, however, are very similar to those for butoxy-substituted compounds.

Table 37

Transition Temperatures (°C) for Terminal Alkoxy-, Alkyl- and Alk-1-ynyl- substituted 1,4-phenyl- and 2,6-naphthyl- ethynes, a Lateral Fluoro-substituted Derivative and a Terminal Bromo-substituted Derivative (**271, 272, 283, 287** and **288**)

Compound	Transition Temperatures (°C)
 **271**	K 126.5 N 171.0 I
 **272**	K 102.5 S_A 108.5 N 144.0 I
 **287**	K 124.0 N 172.0 I
 **288**	K 106.5 N 129.0 I
 **283**	K 106.5 N 145.0 I

Compound **287** is isomeric to compound **271** (terminal groups interchanged) and both compounds have almost identical transition temperatures. Compound **288** melts higher than expected in that by exchanging the butoxy-substituent (compound **287**) for a pentyl-substituent has reduced the melting point by just 17.5 °C and the T_{N-I} value has been reduced by 43.0 °C (which is as expected).

Compound **283** has a terminal bromo-substituent and was intended to be an intermediate, it was therefore a surprise to find such a high T_{N-I} value (145.0 °C). When compared to the pent-1-ynyl-substituted compound (**288**, T_{N-I} value 129.0 °C) compound **283** has a higher T_{N-I} value by 16.0 °C. The T_{N-I} value is very similar to that seen for the butoxy-substituted system (compound **268**, T_{N-I} value 143.0 °C). In fact the terminal cyano-substituted compound (**280**, T_{N-I} value 164.0 °C) has a higher T_{N-I} value by only 19.0 °C. The melting point of compound **283** is identical to that of compound **288** but is higher than for compounds **268** and **280** by 24.5 and 27.0 °C respectively.

3.3 (d) Physical Properties of 2,6-Disubstituted naphthalenes (compounds **254, 259, 260, 267-269, 271, 272, 274, 279-281, 283, 287** and **288**)

The compounds in this class are the most recent prepared and therefore our collaborators at R.S.R.E. (Malvern) are only in the preliminary stages of physical property measurements. However, initial reports of very high birefringence values (~0.45) are extremely encouraging, if not surprising considering the type of substituents present.

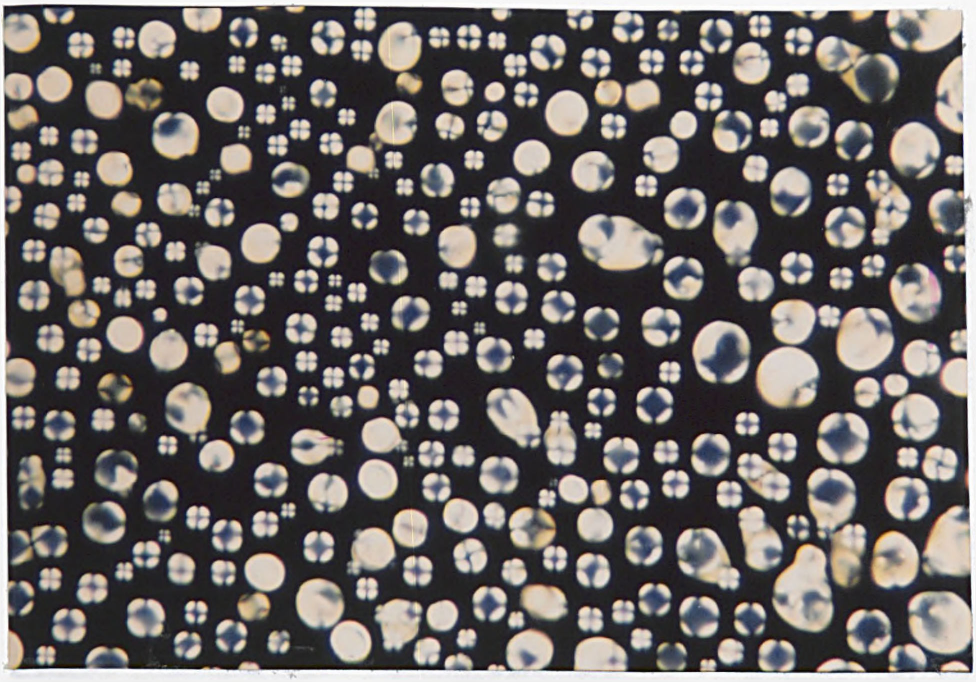
The results, when complete, will provide important information on which groups and combinations of groups give the highest birefringence values. It will be most interesting to compare the birefringence value of compound **260** with that for the analogous compound without the ethyne linkage (**254**). Since terminal bromo-substituted compounds are not often reported in the liquid crystal field then the birefringence value of this compound is keenly awaited. Also the extra birefringence attributable to the second naphthyl moiety in compound **281** over and above those for compounds **260** and **279** will be of interest.

Summary of Section 3.3

The compounds covered by this section all have high melting points (some very high) and high T_{N-I} values (again some very high). This is not surprising in view of the groups used in order to achieve very high birefringence values. The core structure of these compounds is therefore (from initial results) one which is conducive to high birefringence values but leads to high leads to high melting points and high T_{N-I} values. Only the use of terminal alkyl-substituents and lateral fluoro-substituents reduce melting points to any degree with compounds **268** and **280** having the lowest melting points (82.0 and 79.5 °C respectively) but these compounds will probably have reduced birefringence, however, the cyano-substituent in compound **280** should hold up the birefringence value.

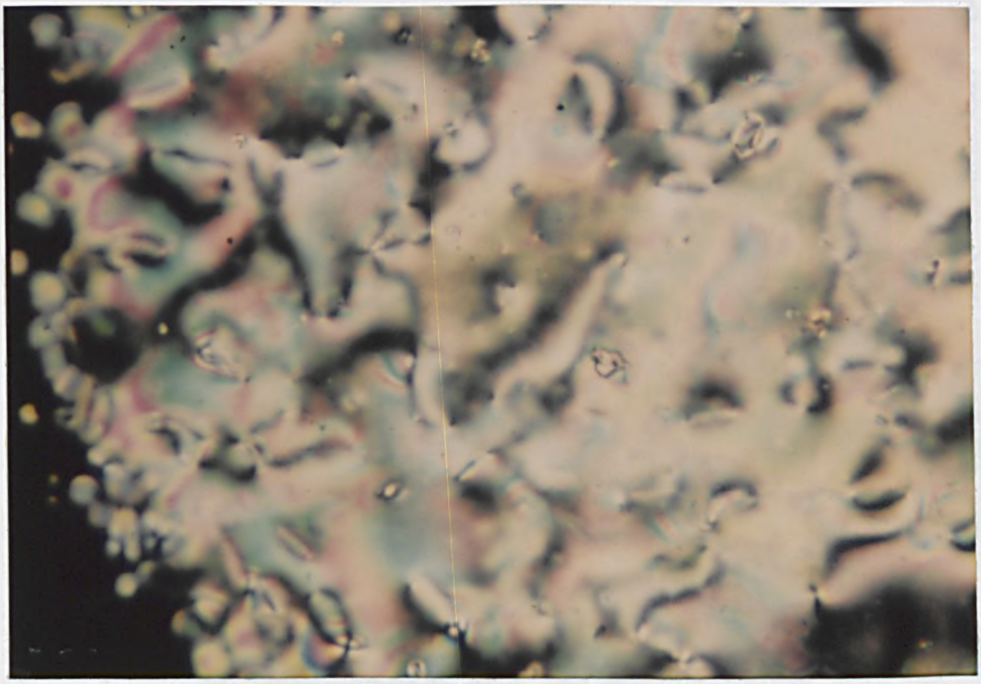
The original ideal aims of high birefringence, low melting points and a T_{N-I} values at or just above room temperature do seem to be mutually exclusive as all the moieties used to obtain higher birefringence values seem to produce higher melting points and higher T_{N-I} values. The best way to achieve these aims may well be to use these compounds because of their high birefringence values and formulate mixtures with compounds of low melting points and low (virtual) T_{N-I} values. If these aims cannot be achieved then perhaps other uses may be found for some of these strongly nematogenic liquid crystalline compounds.

PHOTOMICROGRAPHS



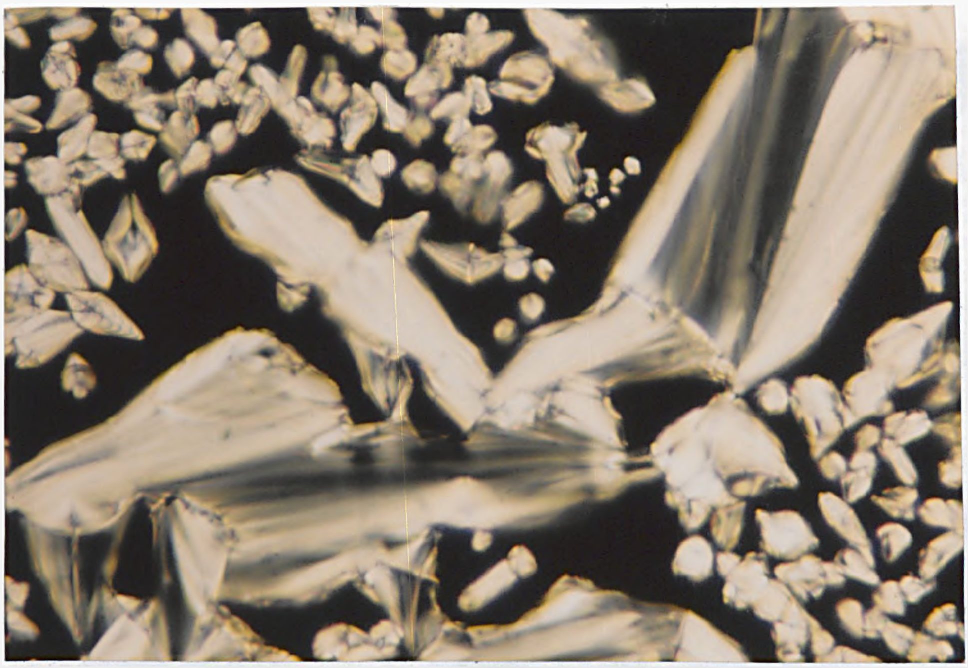
The Formation of Nematic Droplets on Cooling the Isotropic Liquid

Plate 1



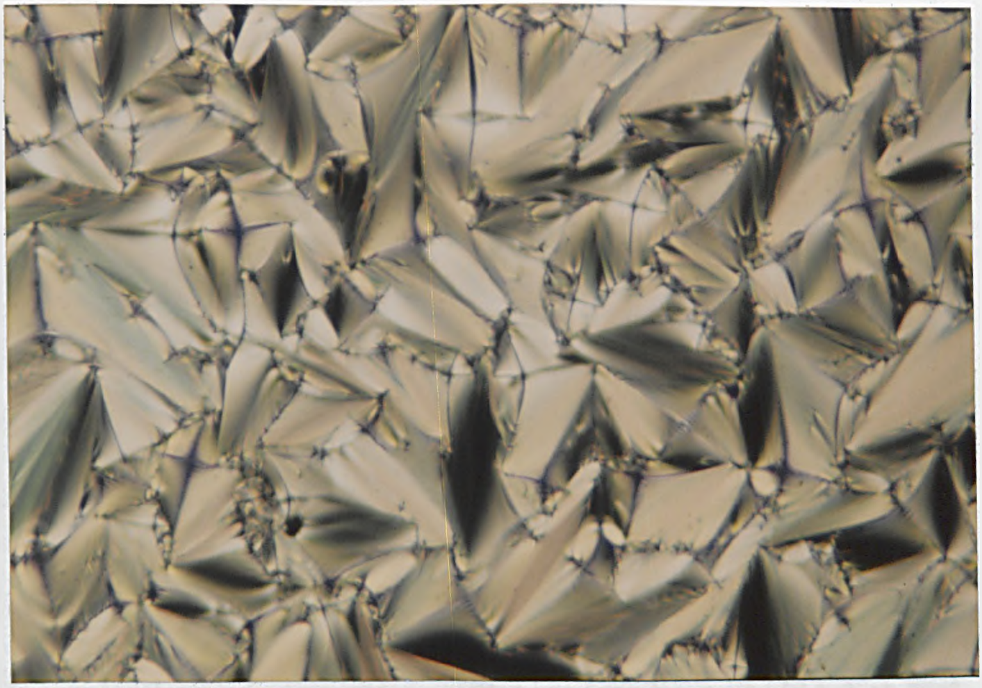
The Schlieren Texture of the Nematic Mesophase

Plate 2



The Formation of Smectic A Batonnet on Cooling the Isotropic Liquid

Plate 3

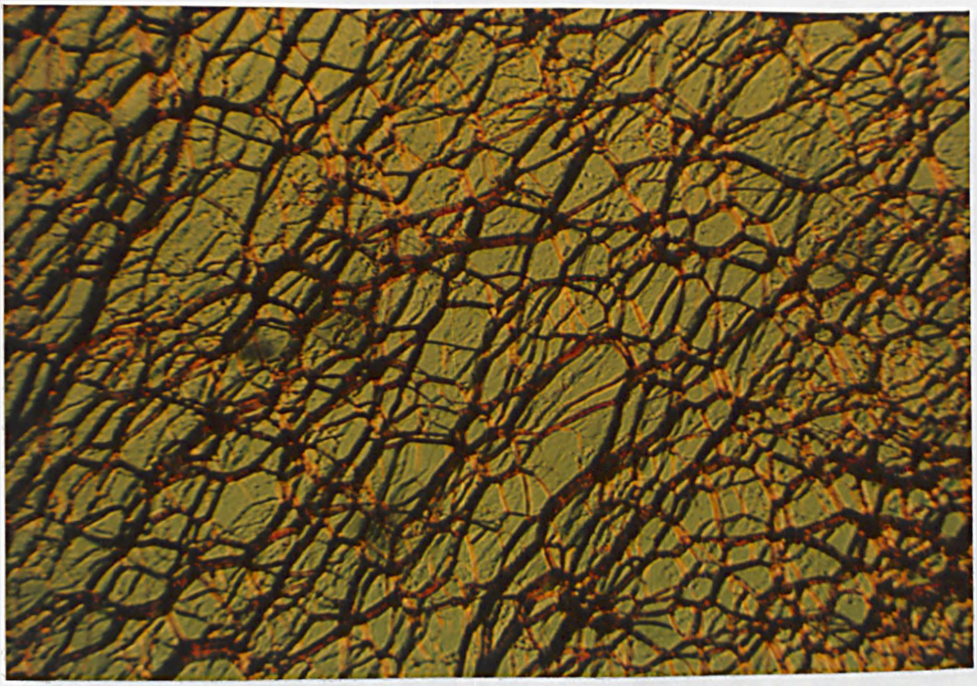


The Focal Conic Fan Texture of the Smectic A Mesophase

Plate 4

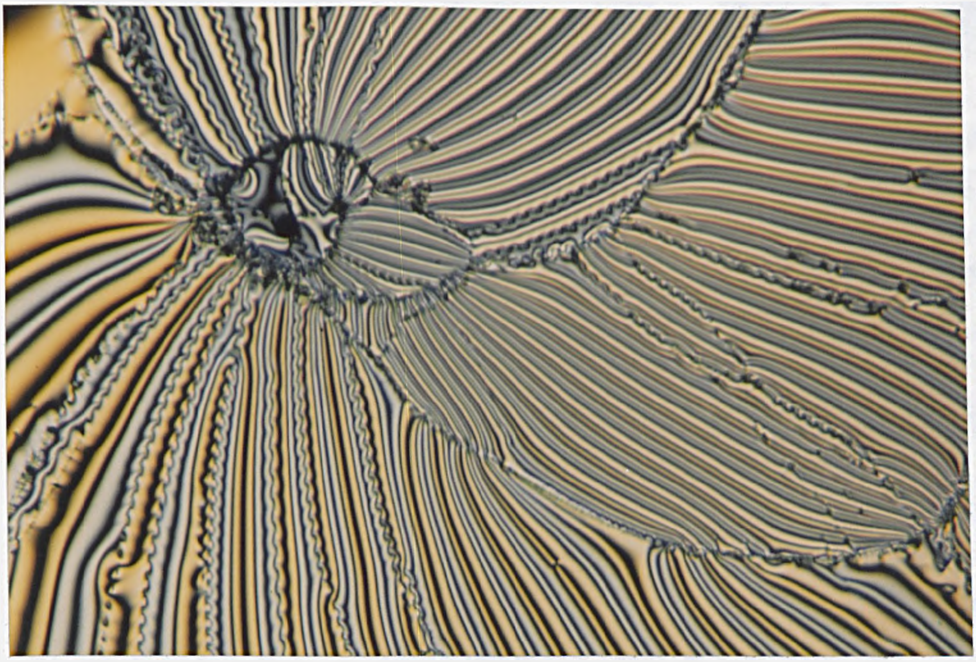
The Focal Conic Fan Texture of the Cholesteric Mesophase

Plate 5



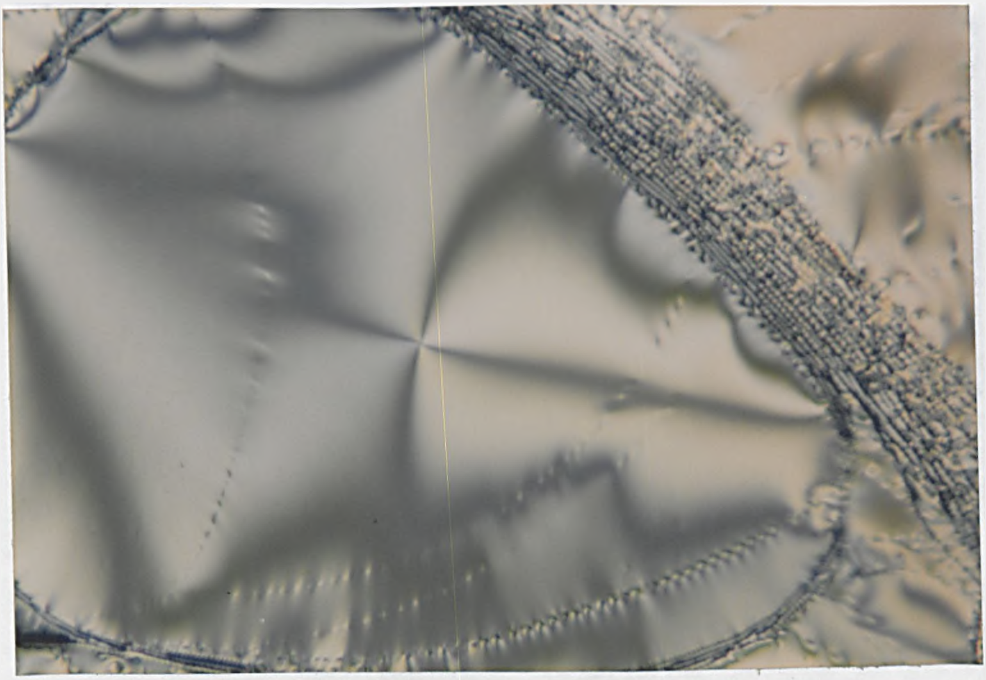
The Grandjean Planar Texture of the Cholesteric Mesophase

Plate 6



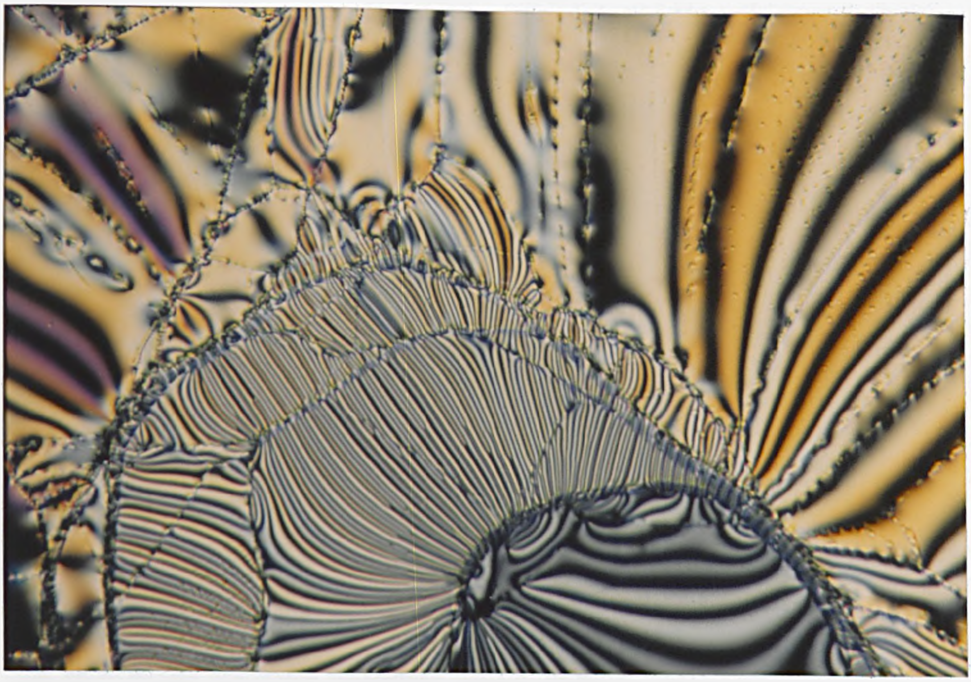
The Schlieren Texture of the Smectic C Mesophase (free-standing film)

Plate 7



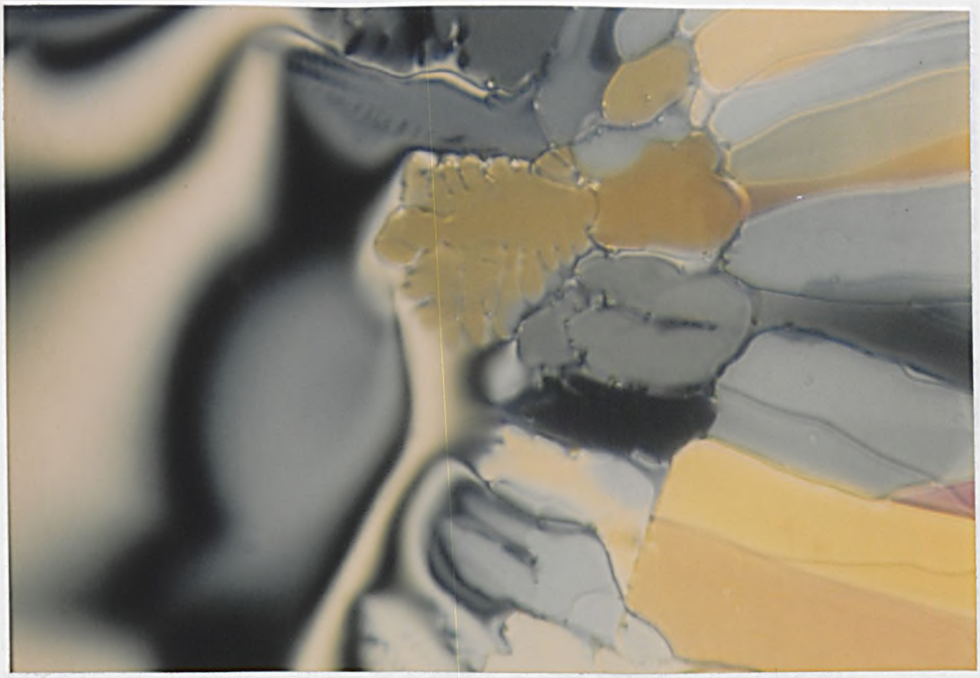
Four Schlieren Brushes of the Smectic C Mesophase (free-standing film)

Plate 8



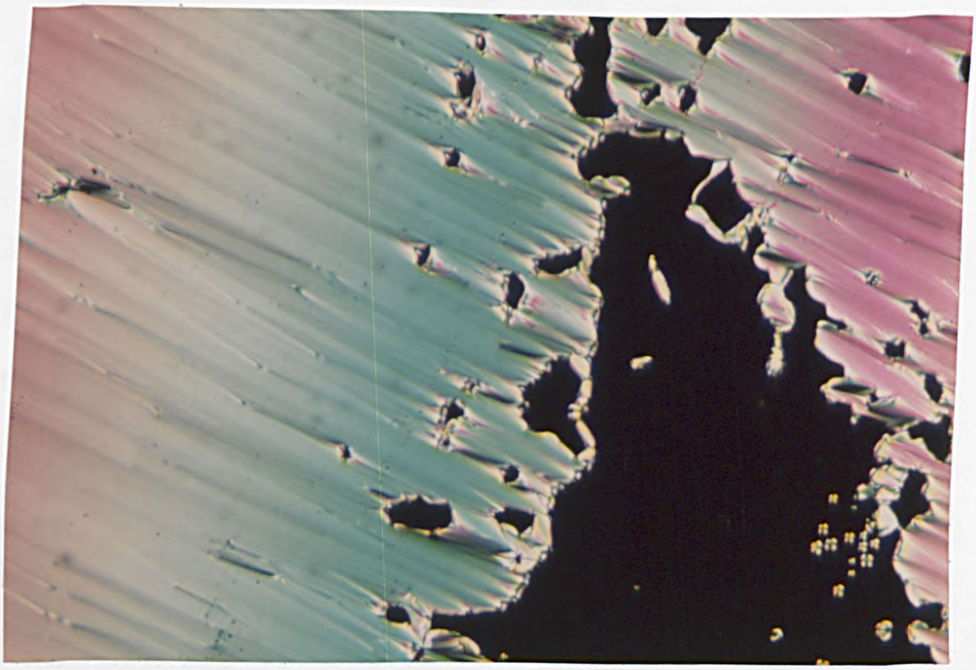
The Schlieren Texture of the Smectic I Mesophase (free-standing film)

Plate 9



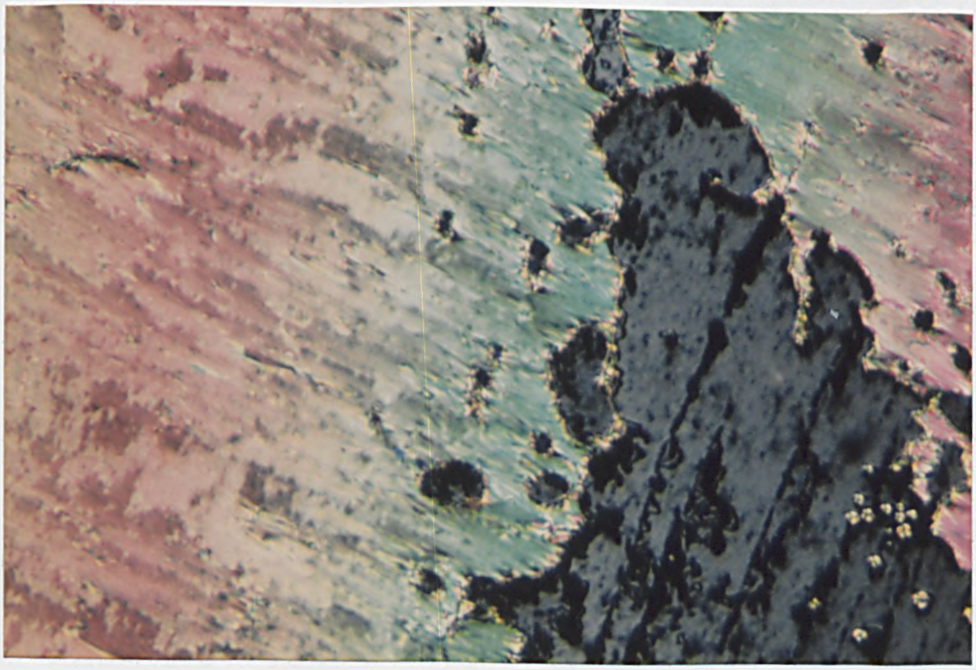
The Dendritic Growth of the Smectic G Mesophase (free-standing film)

Plate 10



The Homeotropic and Focal Conic Fan Textures of the Smectic A Mesophase

Plate 11



The Schlieren and Broken Fan Textures of the Smectic C Mesophase

Plate 12

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