Studies on the sulfation of cellulose α-lipoate and ability of the sulfated product to stabilize colloidal suspensions of gold nanoparticles

Velina Sarbova[a], Andreas Koschella[a], Fei Cheng[b], Stephen M. Kelly[b], Thomas Heinze[* a]

[a] Friedrich Schiller University of Jena, Institute for Organic Chemistry and Macromolecular Chemistry, Center of Excellence for Polysaccharide Research, Humboldtstraße 10, D-07743 Jena, Germany

[b] University of Hull, Cottingham Road, Kingston Upon Hull, UK, HU6 7RX

*E-mail: thomas.heinze@uni-jena.de Tel: +49 3641 948270, Fax: +49 3641 948272

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Abbreviations:

Anhydroglucose unit (AGU)
N,*N*'-Carbonyldiimidazole (CDI)
Cellulose α/β-lipoate sulfate (CLS)
Degree of substitution (DS)
Degree of substitution of lipoate groups (DS_{Lip})
Degree of substitution of sulfuric acid half ester groups (DS_{Sulf})
N,*N*-Dimethylacetamide (DMA)
Dimethyl sulfoxide (DMSO)
Self-assembled monolayers (SAM)
Transmission electron microscopy (TEM)

Abstract

A versatile method for the synthesis of cellulose α-lipoate with a low degree of substitution (DS) has been developed using *N*,*N*-dimethylacetamide (DMA)/LiCl as a solvent and *N*,*N'*-carbonyldiimidazole (CDI) as an esterification reagent. The cellulose α-lipoate with DS of α-lipoate groups of 0.26 was converted with sulfur trioxide-pyridine complex in dimethyl sulfoxide (DMSO) as solvent. The sulfation is accompanied by an unexpected partial oxidation of the disulfide moiety leading to the formation of the corresponding stereoisomers of *S*-oxides. The resulting mixture of water-soluble cellulose α- and β-lipoate sulfate possesses a DS of sulfuric acid half ester groups of 1.78. This cellulose-α/β-lipoate sulfate derivative can be used as an effective stabilizer and solubilizer for the formation of colloidal suspensions of gold nanoparticles formed *in situ* in aqueous solution.

Keywords

esterification of cellulose; sulfur-containing cellulose derivatives; water-solubility; oxidation; gold nanoparticles.

1. Introduction

Cellulose derivatives play an enormous role in both daily life and specialty applications as functional polymers (Heinze & Liebert, 2012). For example, they may serve as viscosity regulators, film-forming agents (Hesse, Liebert & Heinze, 2006), and for the preparation of well-defined surfaces by self-assembly (Mohan et al., 2013; Heinze, Hornig, Michaelis & Schwikal, 2009). Cellulose and cellulose derivatives can also be converted into nano-sized and nano-shaped entities (Wondraczek, Petzold-Welcke, Fardim & Heinze, 2013; Liebert, Kostag, Wotschadlo & Heinze, 2011).

Nanoparticles are gaining an increasing importance for a wide variety of practical applications due to a combination of extraordinary properties mainly determined by their small size, involving quantum confined physical properties, and very large relative surface area, e.g., involving a very reactive surface. Typical applications include heterogeneous catalysis, optics, antibacterial and antimicrobial surfaces, and other biomedical processes (Sharma, Yngard & Lin, 2009; Hermanson, Lumsdon, Williams, Kaler & Velev, 2001; Zhou et al., 2003; Kim et al., 2007; Panacek et al., 2006).

A range of metallic nanoparticles have been prepared by treatment of appropriate precursors with reducing agents (Cheng, Betts, Kelly, Schaller & Heinze, 2013). Unfortunately, nanoparticles prepared in this way tend to aggregate in aqueous dispersions due to their high surface energy. Consequently, the addition of water-soluble stabilizers is indispensable in order to prevent the formation of nanoparticle agglomerates. In the field of "green chemistry" routes of preparation, carbohydrates have been used as both reducing and stabilizing agents, e.g., D-glucose as a reducing agent and starch as stabilizer (Raveendran, Fu & Wallen, 2003; Raveendran, Fu & Wallen, 2006) D-glucose and chitosan (Bozanic, Trandafilovic, Luyt & Djokovic, 2010), maltose and sucrose (Filippo, Serra, Buccolieri & Manno, 2010), heparin (Huang & Yang, 2004). 6-Deoxy-6-(2-aminoethyl)-amino cellulose was used as a stabilizer in

the preparation of silver nanoparticles obtained by reduction of silver nitrate with sodium borohydride (Cheng, Betts, Kelly, Schaller & Heinze, 2013). The high affinity of sulfur to react with and attach itself to noble metals is widely applied to generate well-defined structures, such as self-assembled monolayers, SAMs (Bain, Troughton, Tao, Evall, Whitesides & Nuzzo, 1989). Cellulose α-lipoic acid ester was found to adsorb onto gold surface by the formation of SAMs (Liebert, Hussain, Tahir & Heinze, 2006). The advantage of such films is their uniformity and stability towards mechanical stress and solvolysis.

Based on the pronounced affinity of sulfur towards noble metals, it was of interest to study the potential ability of sulfur-containing cellulose derivatives to stabilize metallic nanoparticles. The lipoate moiety may interact with metal surfaces in several ways: on the one hand, the disulfide moiety may act as complex ligand and, on the other hand, treatment of disulfides with reducing agents affords the corresponding dithiols, which are very useful ligands as well (Cravero, Luna & Barboza, 2011). Cellulose α-lipoate has been prepared previously by conversion of cellulose dissolved in DMA/LiCl with α-lipoic acid by *in situ* activation with either CDI or *p*-toluenesulfonyl chloride (Liebert, Hussain, Tahir & Heinze, 2006). The conversion is completely homogeneous and yields products that are soluble in aprotic dipolar solvents, such as DMSO, even at a low DS (0.11-0.18). However, water-soluble derivatives of cellulose α-lipoate are required in order to stabilize metallic nanoparticles as aqueous colloidal suspensions for practical applications. A facile way to impart water solubility to cellulose α-lipoate is the introduction of ionic moieties. Considering the saponification of ester moieties under alkaline conditions, carboxymethylation, as it is used in case of hydrolytically stable compounds, is not feasible in this case (Koschella, Hartlieb & Heinze, 2011). However, sulfation proceeds under comparably mild conditions that might not interfere with the carboxylic acid ester function as found for dextran [(4-methyl-2-oxo-2*H*-chromen-7-yl)oxy]acetates (Wondraczek, Pfeifer & Heinze, 2010). Therefore, we now report the preparation of cellulose α-lipoate sulfate and its ability to stabilize aqueous colloidal

suspensions of metallic nanoparticles, in this case gold nanoparticles, of a defined size and shape.

2. Experimental Part

Materials for the synthesis, preparation method and structure characterization (FTIR and NMR spectra) of Cellulose α-lipoate **2** can be found in the Supporting Information Section.

2.1 Materials

α-Lipoic acid (Sigma or Acros Organics) and sulfur trioxide-pyridine complex (Sigma-Aldrich) were used as received. DMSO was dried over 4 Å molecular sieves and methanol was dried over 3Å molecular sieves prior to use. Gold (III) chloride hydrate and sodium borohydride ($NaBH_4$, 96 %) were sourced from Aldrich and Fluka, respectively, and used as received without further purification.

2.2 Measurements

FTIR spectra were recorded on a Nicolet Avatar 370 DTGS spectrometer using the KBr technique. The ^{1}H- and ^{13}C-NMR spectra were acquired with Bruker Avance 250 (250 MHz) and Avance 400 (400 MHz) spectrometers in DMSO-d_6 or D_2O at 50 °C with a concentration of at least 5 %, w/w of polymer in solution. Elemental analysis was carried out using a Vario EL III (Elementaranalysensysteme Hanau, Germany). UV–Vis spectra were recorded in the range between 300 – 700 nm using a Perkin Elmer Lambda 25 spectrometer. Ultrapure water with a specific resistance of 18.2 MΩ cm was obtained by reversed osmosis followed by ion-exchange and filtration (UPQ PS system, ELGA, USA). Solution spectra were obtained by measuring the absorption of the prepared colloidal suspensions in a quartz cuvette with a 1 cm

optical path. Transmission electron microscopy (TEM) images were collected using a Jeol 2010 TEM running at 200 kV. Images were obtained with a Gatan Ultrascan 4000 digital camera. The liquid sample was mixed well in a vial, then a 5 µL aliquot was placed on a hydrophilic carbon coated copper grid and allowed to dry in air.

2.3 Methods

*2.3.1 Sulfation of cellulose α-lipoate (**3**)*

The SO_3-pyridine complex (12.6 g, 79.2 mmol, 2 mol/mol OH-group) was added under vigorous stirring to a solution of cellulose α-lipoate **2** (3.0 g, DS_S 0.26, 14.2 mmol) in DMSO (65 mL) under an N_2-atmosphere. The reaction mixture was stirred for 4.5 h at room temperature, then an aqueous solution of sodium acetate trihydrate (27 g of a 24 %, w/w) was added dropwise to the reaction mixture, before being poured into ethanol (450 mL). The resultant polymer precipitate was collected by filtration, washed with ethanol (3 x 250 mL), reprecipitated from aqueous NaCl-solution (2 %, w/w, 60 mL), washed again with a (4:1) of ethanol/water mixture (300 mL), dialyzed for 72 h against water and then freeze-dried to produce a water-soluble product.

Yield: 3.3 g (8.31 mmol, 58.6 %);

DS_{Lip} 0.26, $DS_{Sulfate}$ 1.78 (M 396.91 g/mol, calculated from EA);

^{13}C-NMR spectroscopy (D_2O, 100.63 MHz, δ, ppm): 23.9-24.8 C-9; 25.1-28.6 C-10, 11(c,d); 33.9-35.5 C-8, 11 (a,b), 13; 37.7, 38.2 C-14 (c,d); 57.1 and 59.4 C-12(a,b); 60.3 C-6_{OH}; 62 and 63 C-14(a,b); 66.2 C-6_{Sulf}; 73.2-80.1 C-2,3,4,5_{AGU} and C-12(c,d); 100.7 C-1';

FTIR spectroscopy (KBr, $\tilde{\nu}$, cm^{-1}): 3487 ν OH; 2941 ν $C_{sp3}H$; 1734 ν C=O; 1457-1382 δ CH_2, δ CH_3; 1249 ν_{as} SO_2; 1139, 1113 ν_s C-O-C_{AGU}, ν_s SO_2; 810 ν_s S-O.

2.3.2 Synthesis of α-lipoic acid methyl ester (based on a modified literature procedure Hassan & Maltman, 2012).

Concentrated H_2SO_4 (0.05 mL, 0.01 mol) was added dropwise to a solution of α-lipoic acid (223 mg, 1.05 mmol) and dry methanol (100 mL) under an N_2 atmosphere. The resultant reaction solution was stirred at room temperature overnight and then the solvent was removed under vacuum. The residue was poured into ice-water (100 mL). The resultant precipitate was collected by filtration, washed with saturated aqueous $NaHCO_3$ (3 x 100 mL) and with distilled water (2 x 100 mL) before being dried under vacuum at 40 °C to yield the desired α-lipoic acid methyl ester (soluble in DMSO at 50-60 °C).

Yield: 185 mg (0.84 mmol, 80.0 %)

^{1}H-NMR Spectroscopy (DMSO-d_6, 400 MHz, δ in ppm): 1.4 (CH_2, H-5); 1.56 (CH_2, H-4); 1.56 und 1.67 (CH_2, H-6); 1.88 und 2.42 (CH_2, H-8); 2.31 (CH_2, H-3); 3.09-2.21 (CH_2, H-9); 3.59 (CH_3, H-1; CH, H-7).

^{13}C-NMR Spectroscopy (DMSO-d_6, 100.63 MHz, δ in ppm): 24,5 (CH_2, C-4); 28,3 (CH_2, C-5); 33,4 (CH_2, C-3); 34,3 (CH_2, C-6); 38,4 (CH_2, C-9); 40,2 (CH_2, C-8); 51,4 (OCH_3, C-1); 56,3 (CH, C-7); 173,4 (C=O, C-2).

2.3.3 Mixture of α-lipoic acid methyl ester and SO_3 pyridine complex for NMR analysis

α-Lipoic acid methyl ester (33 mg, 0.15 mmol) was first dissolved in DMSO-d_6 (1.2 mL) at 60 °C, then after cooling the reaction solution to room temperature, an SO_3-pyridine complex (48 mg, 0.30 mmol) was added to the mixture, which was stirred for 3 h at room temperature before acquisition of the NMR spectrum.

^{13}C-NMR Spectroscopy (DMSO-d_6, 150.9 MHz, δ in ppm): 24.4-24.7 (CH_2, C-4); 26.2 and 26.9 (CH_2, C-6 c and d); 27.8-28.7 and 28.7 (CH_2, C-5); 33.4-33.5 (CH_2, C-3); 33.9 and 34.3 (CH_2, C-8 c and d); 35.2-35.9 (CH_2, C-6 a and b, C-8); 36.9 and 37.2 (C-9 c and d); 51.6 (OCH3, C-1); 55.7 and 58.1 (CH, C-7 a and b); 61.9 and 63.1 (CH2, C-9 a and b); 74.9 and 77.8 (CH2, C-9 c and d); 127.4-147.4 (pyridine and pyridinium salts); 173.7 (C=O, C-2).

2.3.4 Preparation of gold nanoparticles in the presence of cellulose α/β-lipoate sulfate

A 0.5 % cellulose α/β-lipoate sulfate solution (10 mL) was added to a solution of gold (III) chloride hydrate (85.0 mg) in ultrapure water (5 mL) at room temperature. The resultant reaction mixture was stirred for 30 min, then a sodium borohydride solution (200 mM, 5 mL) was added dropwise to the reaction mixture under strong stirring, which resulted in the formation of a red solution after 10 min.

3. Results and Discussion

3.1 Studies on sulfation of cellulose α-lipoate

The preparation of cellulose α-lipoate was carried out according to a modified literature procedure (Liebert, Hussain, Tahir & Heinze, 2006). Thus, cellulose dissolved in DMA/LiCl was allowed to react with a previously prepared mixture of α-lipoic acid and CDI in DMA. The molar ratio of anhydroglucose unit (AGU):α-lipoic acid:CDI was 1:1:1. Conversion for 16 h at 60 °C afforded cellulose α-lipoate with a degree of substitution, DS_{Lip} of 0.26 (sample **2**). The polymer forms highly viscous solutions in DMSO. The structure was confirmed by FTIR- (Figure 1) and NMR spectroscopy (Figure 2) including a HSQC-DEPT NMR spectrum (Figure S1, Supporting Information Section).

(Scheme 1)

The sulfation of cellulose α-lipoate was achieved by treatment with a sulfur trioxide-pyridine complex in DMSO. The crucial issue is the subsequent conversion of the sulfuric acid half ester formed to the corresponding sodium salt, which is the form of the polymer that will be stable upon storage. Therefore, neutralization must be carried out in order to prevent the undesired cleavage of the α-lipoate esters. An excess of aqueous sodium acetate solution neutralizes sulfuric acid half ester moieties efficiently without cleaving any of the carboxylic acid ester. Precipitation in ethanol, washing of the precipitate with ethanol and dialysis against water affords the corresponding CLS (sample **3**). The DS_{Sulf} value was calculated under the assumption that the DS_{Lip} remains constant during the sulfation reaction. A DS_{Sulf} value of 1.78 was found for sample **3**.

An additional strong signal for the sulfate groups could be observed at about 1100 cm^{-1} ($\nu_s SO_2$) in the FTIR spectra of the product **3** (Figure 1). Further signals for the sulfur-containing moiety are visible at 1249 cm^{-1} ($\nu_{as} SO_2$). However, overlapping with cellulose signals occurs in this region as well as in the region around 810 cm^{-1} (ν_s S-O). Characteristic vibrations of the polymer backbone are found at 3487 cm^{-1} (νOH), at 2941 cm^{-1} ($\nu C_{sp3}H$), at 1457-1382 cm^{-1} (δCH_2, δCH_3) and at 1139 cm^{-1} and 1113 cm^{-1} (ν_s C-O-C_{AGU}). Vibration of the α-lipoate moiety is still detectable at 1734 cm^{-1} (ν C=O). An absorption band at 2560-2570 cm^{-1} could not be observed in this spectrum and so it can be concluded that there are no thiol groups present in the product **3**.

(Figure 1)

The products were investigated by means of one- and two-dimensional-NMR experiments in D_2O at 50 °C. It must be mentioned that well-resolved NMR spectra could be recorded from dialyzed samples only because salts decrease the resolution to a remarkable extent. Nevertheless, the ^{13}C-NMR spectrum of product **3** shows a typical appearance of a polyelectrolyte with broad peaks (Figure 2).

The sulfation of the polymer is confirmed by the presence of a low-field shifted peak (66.3 ppm, C-6_{Sulf}) for position 6 of the modified repeating unit bearing a sulfuric acid half ester moiety. Signals for the AGU are found in the range from 73.2 ppm to 80.3 ppm (carbon atoms 2-5 of the AGU). Additional peaks appear between 76.8 and 78.9 ppm indicating functionalization of the secondary hydroxyl groups. The high-field shifted signal at 100.7 ppm is assigned to position 1' adjacent to the modified C-2 compared to the anomeric C-1 of the starting material **2** (Figure 2). The unmodified position 6 is assigned at 60.1 ppm (C-6_{OH}) and the lipoate-substituted position 6 (C-6_{Lip}) is difficult to detect as it is the case for the starting material cellulose α-lipoate **2** (see supporting information).

(Figure 2)

Signals resulting from the alkyl chain of the carboxylic acid moiety are apparent in the range from 24.5 ppm to 35.6 ppm (CH_2-groups, Figure 2). However, the chemical shifts are slightly different compared to those of the starting material **2**. Furthermore, a peak for C-13 (CH_2) could not be observed at ca 40 ppm, on the one hand, and three additional signals appear in the area between 59.4 and 62.9 ppm next to the signal expected for the methine group C-12 (ca. 57 ppm) of the lipoate substituent on the other hand. It can be concluded from the DEPT135-NMR measurement that these additional signals should be attributed to two methylene- (CH_2) and one methine group (CH, Figure 2). These signals do not correlate with the chemical structure of cellulose α-lipoate sulfate. It must be taken into account that

unexpected side reactions have taken place during the conversion of cellulose α-lipoate **2** with the sulfur trioxide pyridine complex. It is known that oxidation of acetylated monosaccharides, according to the Parikh-Doering reaction, occurs in the presence of the sulfonating reagent in DMSO leading to the formation of carbonyl groups and unsaturated moieties in the pyranose ring (Cree, Mackie & Perlin, 1969). Hence, the appearance of further signals corresponding to new CH_2 and CH signals that are shifted to a lower field compared to the AGU must be elucidated. The additional peaks observed are high-field shifted instead and no further chemical shifts are observed (Figure 2). Thus, oxidation of the polymer backbone must play a minor role or does not take place at all under these reaction conditions. The possibility of oxidation of the disulfide moiety by SO_3/DMSO, according to the Parikh-Doering mechanism, should also be taken into consideration, whereby, the products should contain sulfoxide- or sulfone structures. However, oxidation of thioctic acid is scarcely described in the literature (Stary, Jindal & Murray, 1975; Müller, Knaack, & Olbrich, 1997) and there is no information about the capability of SO_3 to oxidize structural features bearing disulfide bonds.

In order to study the capability of the mixture of sulfur trioxide pyridine complex and DMSO to oxidize disulfides, α-lipoic acid methyl ester was dissolved in DMSO-d_6, mixed with sulfur trioxide pyridine complex in a molar ratio of 1:2 and allowed to react for 3 h at room temperature under stirring. The mixture was then investigated by means of one- and two-dimensional NMR-spectroscopy and compared with the NMR data available in the literature (Müller, Knaack & Olbrich, 1997). According to the NMR spectra it becomes clearly obvious that oxidation of the dithiolane ring takes place simultaneously during the sulfation of cellulose α-lipoate in DMSO (Figure 2). It is assumed that a conversion to thiosulfinate mainly occurrs leading to the formation of cellulose β-lipoate sulfate (Figure 3).

(Figure 3)

β-Lipoic acid refers to a mixture of diastereomeric *S*-oxides of α-lipoic acid, i.e., a thiosulfinate (R-S(O)-SR'). Since R/S-α-lipoic acid was used as reagent and the sulfoxide groups represent a chiral center in the molecule, then eight stereoisomers should be expected overall, wherefrom signals for four diastereomers should be visible in the NMR spectrum (Figure 3 left, a-d). The presence of the isomeric compounds a-d of CLS **3** can be located by the presence of the signals in the range from 37.7 to 38.2 ppm [C-14(c,d)], at 57.1 and 59.4 ppm C-12(a,b), and at 62 and 63 ppm [C-14(a,b)] (Müller, Knaack & Olbrich, 1997). Still, an exact assignment of the NMR-peaks to each isomer of substance **3** requires model compounds with known structure. Therefore, Figure 2 represents a proposal for the allocation of the observed peaks. Due to the fact that the ratio between the α-and β-lipoate cannot be determined, the sulfation product of cellulose α-lipoate is now called cellulose α/β-lipoate sulfate (CLS).

Taking into account the fact that unintended thiosulfinate moieties are formed, in addition to the intended sulfation of hydroxyl groups, then another result can be explained. As mentioned before, the sulfuric acid half esters had been carefully neutralized in order to make the polymer stable upon storage. However, the initially neutral sample solutions became acidic after a few days of storage. Owing to the properties of thiosulfinates, this behavior could be explained now. It is reported that these compounds are not stable in the dissolved state, in particular in the presence of acids and nucleophilic substances (Auger, Lallau-Keraly & Belinsky, 1990; Shen, Xiao & Parkin, 2002).

3.3 Preparation of gold nanoparticles in the presence of cellulose α/β-lipoate sulfate

Disulfide- and thiol-containing compounds are known to spontaneously adsorb onto gold surfaces by forming an adsorbate-substrate sulfur-metal bonds (Bain, Troughton, Tao, Evall, Whitesides & Nuzzo, 1989). Thus, a chemisorption of cellulose α/β-lipoate sulfate (CLS)

on gold involving the thiosulfinate (partially oxidized) and disulfide moieties should be expected. In addition, disulfide can be reduced to the dithiol by the $NaBH_4$ applied for the reduction of $HAuCl_4$, and hence, a further functionality for such interactions can be generated. However, no interactions should be expected in case of the sulfate groups, which serve to provide water-solubility of the cellulose derivative.

Preliminary research on the preparation of gold nanoparticles in the presence of CLS is shown in Scheme 2. When the $HAuCl_4$ solution was added to the CLS solution, the reaction mixture solution became yellow. No color change could be observed even after the solution was heated at 75 °C overnight, suggesting that the ability of CLS as a reducing agent is very weak. However, when $NaBH_4$ solution was added to the $HAuCl_4$ – CLS solution, the color changed immediately from yellow to red, indicating the reduction reaction occurs readily and quickly. The colloidal suspensions can be stable for four weeks without the formation of any precipitate.

(Scheme 2)

The UV-vis adsorption spectra of the reaction mixture of $HAuCl_4$ and CLS before and after adding $NaBH_4$ are shown in Figure 4. No adsorption peak can be found in the wavelength range of 300 – 700 nm (Figure 4a) for the reaction solution before the addition of $NaBH_4$, which is indicative of the fact that no reduction of Au^{3+} occurs in the presence of CLS alone. After adding $NaBH_4$, two adsorption bands can be observed at ca 439 and 525 nm (Figure 4b). The adsorption band at 525 nm is a typical of surface plasmon resonance band for AuNPs, confirming the formation of gold nanoparticles reduced by $NaBH_4$. (Wei, Qi, Tan, Liu & Wang, 2010). The UV-vis absorption peak observed at 525 nm is probably attributable to the normal surface resonance peak of the gold nanoparticles with some CLS ligands bound to the surface of the gold nanoparticles. The particle size of gold nanoparticles affects the position of UV-vis

absorption peak and so the UV-vis spectra will exhibit a red-shift, if small nanoparticles aggregate to form bigger nanoparticles. (You, Hu, Zhou, Zhang & Kordo, 2013). The peak observed at 439 nm may be attributable to the presence of small gold nanoparticle aggregates. However, further work will be conducted to investigate the exact mechanism for the formation of this second absorption peak. The TEM image of the CLS-stabilized gold nanoparticle suspension and the particle size distribution are shown in Figure 5. It can be seen that spherical or close-to-spherical nanoparticles are separated from each other and well dispersed. The corresponding histogram for the particle size distribution shows that the nanoparticle size is mainly in the range of 2.0 – 7.0 nm. A black precipitate is formed immediately after the addition of the $NaBH_4$ solution to the $HAuCl_4$ solution in the absence of CLS. All these facts indicate that CLS molecules protect and stabilize the gold nanoparticles very effectively and also prevent their agglomeration. Thus, it can be concluded that stable aqueous suspensions of gold nanoparticles can be successfully synthesized by reduction of $HAuCl_4$ in the presence of CLS molecules.

(Figure 4)

(Figure 5)

4. Summary and Conclusions

Cellulose-α-lipoate with a low substitution density (DS_{Lip} = 0.26) was synthesized homogeneously in DMA/LiCl using CDI for the *in situ* activation of the carboxylic acid (Liebert, Hussain, Tahir & Heinze, 2006). Infrared (IR) spectroscopy shows that the dithiolane ring remains intact during the conversion. Furthermore, it was possible to analyze the product

structure by means of one- and two-dimensional nuclear magnetic resonance (NMR) without subsequent peracylation of the compound. Sulfation of cellulose α-lipoate yields a water-soluble product. No evidence for the oxidation of the AGU by combining SO_3-pyridine complex and DMSO was found. Instead, NMR investigations of α-lipoic acid methyl ester revealed that the disulfide moiety of the α-lipoate substituent participates in side reactions, whereby it is oxidized, in the course of the conversion leading to CLS, to a mixture of stereoisomeric *S*-oxides of the sulfated cellulose α/β-lipoate. Gold nanoparticles with particle size 2.0 – 7.0 nm can be successfully synthesized by reduction of $HAuCl_4$ in the presence of CLS molecules.

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