Influence of Transition-Metal Ions on the Aggregation Behavior of a Single-Chained Ammonium Amphiphile Carrying an *o*-Hydroxyazobenzene Unit

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A novel, single-chained ammonium amphiphile that carries an *o*-hydroxyazobenzene unit at the terminus of its hydrophobic chain has been synthesized. This compound forms ordered thread-like aggregates upon dispersion in water. These aggregates exhibit a phase transition at 56 °C. The *o*-hydroxyazobenzene unit binds several transition-metal ions in a 2:1 stoichiometry. Binding of these metal ions results in a lowering of the critical aggregation concentration. From the changes in the UV absorption spectrum it is concluded that the Cu^{2+} complex forms more tightly packed aggregates in water than the Zn^{2+} and Ni^{2+} complexes.

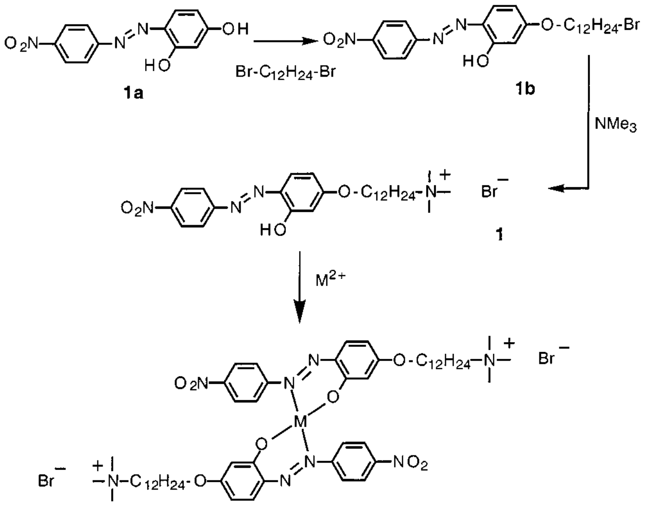
Surfactants form micro-heterogeneous dispersions in water as a result to their self-assembling behavior. These self-organized structures like micelles and bilayer vesicles find applications in many fields ranging from detergency to oil-recovery technology. Bilayer vesicles have also been proposed as drug delivery systems.[1−3] Micelles and bilayer structures from surfactants that bind metal ions in their headgroup region have been shown to exhibit catalytic activity toward hydrolytic reactions.[4−7] These systems can also be used to purify water from metal-ion contaminants by removing the micelle-bound metal ions by ultra-filtration techniques.[8−10] Furthermore, the binding of different metal ions to aqueous surfactant dispersions has been shown to affect the aggregate morphology in a number of cases.[11−14]

Kunitake et al.[15] and Singh et al.[16] incorporated azobenzene units into the hydrophobic tails of single-chained surfactants which can bind metal ions in their headgroup region. Binding of metal ions induces aggregation of these surfactants resulting in a blue shift of the azobenzene π-π* absorption maximum. Suh et al.[12] have synthesized surfactants with an *o*,*o*′-dihydroxyazobenzene headgroup. In these surfactants two metal ions are bound by the azobenzene unit itself resulting in coordinatively polymerized structures.

In this paper we report the synthesis of a novel, single-chained ammonium surfactant carrying an *o*-hydroxyazobenzene group at the terminus of the hydrophobic chain. The aggregation behavior of this compound in water has been studied by conductometry, electron microscopy, differential scanning calorimetry, UV absorption spectroscopy, and ^{1}H-NMR spectroscopy. Furthermore, the effect of metal-ion binding on the aggregate stability in water has been investigated. Also the formation of ion-pair amphiphiles with sodium dodecyl sulfate has been studied.

Results and Discussion

The novel, single-chained ammonium amphiphile **1** containing a terminal *o*-hydroxyazobenzene unit which is able to bind transition-metal ions has been synthesized. The synthetic pathway and the molecular structure are given in Scheme 1. The coupling of 2,4-dihydroxy-4′-nitroazobenzene with 1,12-dibromododecane results in the formation of many products. However, one of the first products to be formed is the monoalkylated compound **1b**. Therefore, the reaction time should be no longer than two hours. Reaction of this compound with NMe_3 leads to the amphiphilic compound **1**. At neutral pH, the Krafft point of compound **1** is found at 27°C.



Scheme 1. Synthetic pathway and molecular structure of compound **1** and its metal-ion complex

In water this compound forms thread-like structures with diameters of approximately 70 Å, some of which have a strange bud at one of their ends as was observed by cryo-electron microscopy (see Figure 1). A phase transition is observed at 56°C with DSC and with ^{1}H-NMR spectroscopy (see Figure 2). From the increase in the sharpness

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of the peaks in the NMR spectrum between 50 and 60°C it is concluded that the molecules undergo a transition to a more mobile state.

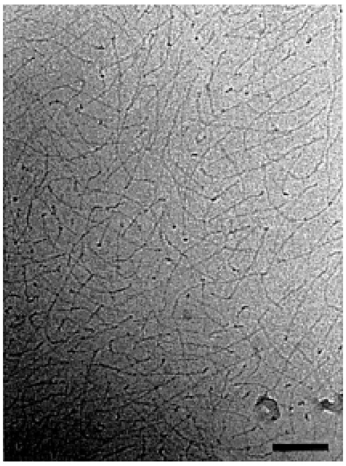

Figure 1. Cryo-electron micrograph of an aqueous dispersion of **1**; the bar represents 85 nm

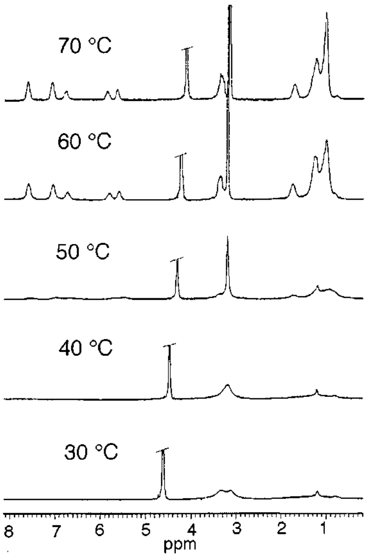

Figure 2. 200-MHz ^{1}H-NMR spectra of dispersions of **1** in D_2O at different temperatures; the residual HDO signal at $\delta \approx 4.5$ has been cut off

At neutral pH the critical aggregation concentration (cac) is found to be about 0.1 mM at 20°C as was determined by conductivity measurements. The concentrations used for UV absorption spectroscopy are far below the cac and an absorption maximum at 395 nm is observed. The same spectrum is observed in ethanol indicating that the molecules are present in a non-aggregated state in aqueous solution. When the concentration in water is increased to far above the cac, the absorption maximum is seen to shift to 350 nm. This blue-shifted absorption maximum is indicative for the presence of azobenzene aggregates in which the transition dipoles lie (anti)parallel with respect to each other, so-called H aggregates.[17,18] This means that the formed aggregates are highly ordered.

When copper(II) acetate is added to an aqueous solution of **1** under its cac, aggregation is immediately induced as is observed by the appearance of a blue-shifted absorption maximum at 350 nm (see Figure 3a). Apparently, the binding of Cu^{2+} results in a concomitant supramolecular aggregation. This was also confirmed by conductivity measurements. Electron microscopy shows that the aggregate morphology is not affected by the binding of Cu^{2+}. When copper(II) acetate is added to an ethanolic solution of **1** two maxima at 366 and at 462 nm are observed (see Figure 3b) which is attributed to binding of Cu^{2+} ions without supramolecular aggregation.

The blue shift of the absorption maximum in water is almost complete when 0.6 equivalent of Cu^{2+} ions has been added. This means that Cu^{2+} binds almost quantitatively in a 1:2 stoichiometry. The proposed structure of the formed complex is given in Scheme 1. The Zn^{2+} and Ni^{2+} ions bind less strongly to **1** and a tenfold excess of nickel(II) acetate or zinc(II) acetate is needed to obtain the spectrum of the aggregated species. It is a fairly general phenomenon that the equilibrium constant for the formation of analogous complexes of divalent cations with ligands containing a nitrogen donor decreases when going from Cu^{2+} to Ni^{2+} or Zn^{2+}.[18] It cannot be excluded that the acetate ions will also induce aggregation by screening the headgroup repulsions. However, the difference in aggregation behavior observed between addition of copper(II) acetate and nickel(II) acetate indicates that binding of the metal ion is the dominant process in promoting the aggregation.

Furthermore, it is observed that the extent of the blue shift is different for the three complexes. For Cu^{2+}, Ni^{2+}, and Zn^{2+} the blue-shifted absorption maxima lie at 350 nm, 364 nm, and 378 nm, respectively (see Figure 3c). According to the exciton theory proposed by Kasha[17] the extent of the blue shift of the UV absorption maximum is strongly dependent on the distance between the azobenzene units and on their relative orientation. The observed differences in absorption maximum for the investigated metal ions might therefore reflect the average stacking distances between the azobenzenes in the formed aggregates. This would mean that the **1**-Cu^{2+} complex forms the most ordered supramolecular aggregates.[19] In case of Cu^{2+} or Ni^{2+}, square-planar coordination is most likely; for Zn^{2+} complexation, tetrahedral coordination is also possible. This might be responsible for the smaller blue shift found in case of the Zn^{2+} complexation (see Figure 3c). Two effects are therefore important: the binding strength, which determines how effective a metal ion is in bringing together the chromophores at a stacking distance, and the aggregation strength between the complexes, which depends also on the coordination geometry, i.e. whether the complex is square-planar or tetrahedal.

The aggregates of the **1**-Cu^{2+} complex have the same blue-shifted absorption maximum as the aggregates of pure **1**. This means that incorporation of Cu^{2+} ions does not alter the average azobenzene–azobenzene distances in the aggregate. The binding of Zn^{2+} and Ni^{2+}, however, results in a reduction of the blue shift with respect to that of the

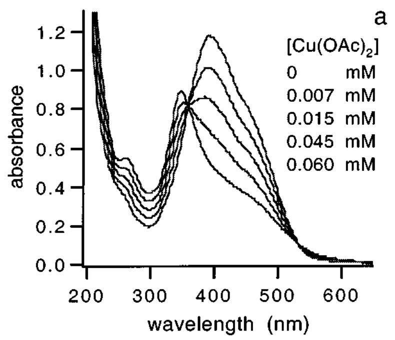

Figure 3a. UV absorption spectra of an aqueous dispersion of **1** (0.075 mM) before and after the addition of $Cu(OAc)_2$

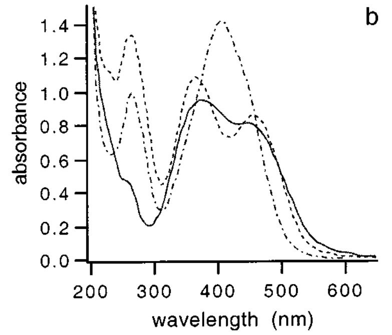

Figure 3b. UV absorption spectra of ethanolic solutions of **1** (0.075 mM) without metal ions (- · - ·) and after the addition of $Cu(OAc)_2$ (- -) and after the addition of $Ni(OAc)_2$ (——)

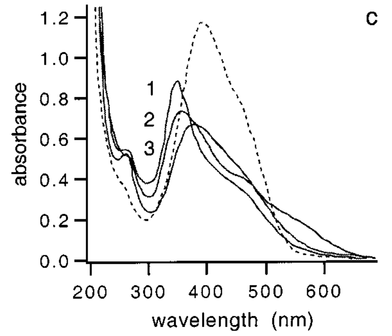

Figure 3c. UV absorption spectra of aqueous dispersions of **1** (0.075 mM) before (- -) and after the addition of excess $Cu(OAc)_2$ (1), $Ni(OAc)_2$ (2), and $Zn(OAc)_2$ (3) in excess

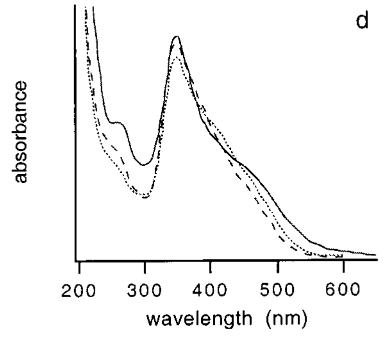

Figure 3d. UV absorption spectrum of an aqueous dispersion of **1** at 0.3 mM, a concentration far exceeding the cac (· ·); UV absorption spectra at low concentrations (0.075 mM) in the presence of $Cu(OAc)_2$ (——) and in the presence of SDS (- -)

aggregates of pure **1**. This indicates that the binding of these ions hampers the optimal packing of the azobenzenes in the aggregates.

When a large excess of vesicles of didodecyldimethylammonium bromide (DDAB) is added to a solution of **1**-Cu^{2+} aggregates, no spectral changes occur indicating that the **1**-Cu^{2+} aggregates are very stable and no mixing of monomers occurs. When vesicles of DDAB are added to **1**-Zn^{2+} or **1**-Ni^{2+} aggregates, the blue shift is immediately lost due to the formation of mixed aggregates in which there is no longer any stacking of the azobenzenes. This demonstrates that the **1**-Zn^{2+} or **1**-Ni^{2+} aggregates are indeed less stable than the **1**-Cu^{2+} aggregates.

The spectral shift caused by the aggregation induced by the binding of Cu^{2+} forms an effective means to detect very low concentrations of Cu^{2+} in water. When a concentration of 50 mM of compound **1** is present in the cuvette, a concentration of 10 μM of Cu^{2+} can easily be detected.

The addition of one equivalent of sodium dodecylsulfate (SDS) to a solution of **1** at a sub-micellar concentration also results in a blue shift of the absorption maximum from 395 nm to 350 nm as a result of the formation of ion-pair amphiphiles (Figure 3d). These ion-pair amhiphiles have a lower critical aggregation concentration than the parent amphiphiles. This is caused by the electrostatic attraction between the headgroups.[20,21]

Interestingly, the UV absorption spectrum, which is obtained for **1** in the presence of Cu^{2+}, is rather similar to the spectrum obtained in the presence of sodium dodecylsulfate (SDS) or for the pure compound **1** at concentrations far exceeding the cac (see Figure 3d). In the presence of Cu^{2+} ions the azobenzenes are forced in an antiparallelly interdigitated configuration (Figure 4). This suggests that in the absence of metal ions the azobenzenes are also interdigitated in the formed aggregates. This interdigitation of azobenzene units in self-aggregated structures has been reported before.[17,22] The interdigitation of the azobenzenes results in an increased distance between the alkyl chains (which might induce tilting of the alkyl chains). SDS probably fills these empty spaces very well and therefore these ion-pair aggregates give the same spectral blue shift as the aggregates of pure **1** and the **1**-Cu^{2+} complex.

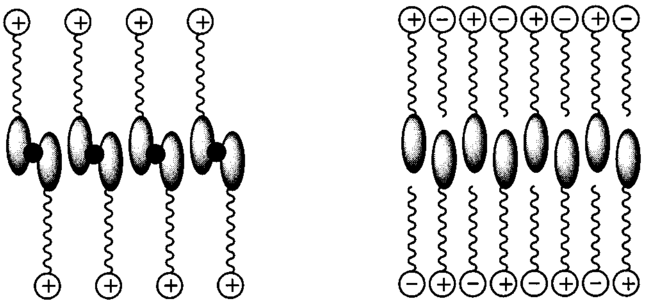

Figure 4. Schematic representation of possible aggregate structures of **1** in the presence of Cu^{2+} (left) and SDS (right)

If the azobenzenes are actually interdigitated, it is difficult to imagine how these molecules form the thread-like structures, since the molecules cannot pack as conventional surfactants in a rod-like micelle. Possibly, these thread-like structures consist of narrow bilayer ribbons with the lateral edges exposed to the aqueous phase. This would expose part of the polar azobenzene units in the aggregate to the water. This might compensate for the unfavorable interaction of the exposed alkyl chains.

Conclusions

The novel *o*-hydroxyazobenzene-containing ammonium amphiphile **1** forms thread-like aggregates in water which exhibit a phase transition at 56°C. Aqueous dispersions of **1** exceeding the critical aggregation concentration show a blue-shifted absorption maximum due to the formation of H aggregates of the azobenzene units. It has been shown that binding of metal ions can occur in the interior of the formed aggregates. This does not seem to alter the aggregate morphology. Binding of Cu^{2+} ions results in a strong decrease of the cac and a strong stabilization of the formed aggregates. Ni^{2+} and Zn^{2+} are less strongly bound by this amphiphile and binding of these ions results in the formation of less stable and less ordered aggregates. Compound **1** readily forms ion-pair amphiphiles with sodium dodecylsulfate. The azobenzene units in the ion-pair aggregates are probably similarly interdigitated as in the Cu^{2+}-ion-complexed aggregates and as in the aggregates of pure **1**.

Experimental Section

General: Aqueous dispersions were prepared by slightly heating and shaking of the solid material in water. The water was purified by filtration through a Seralpur pro 90C purification system. − For the differential scanning calorimetry measurements (Perkin-Elmer DSC 7) 1% (w/w) sample solutions were prepared. A scan rate of $10°C\cdot min^{-1}$ was used. − The critical aggregation concentration was determined by measuring the specific conductivity of the solution of **1** as a function of the concentration. A Philips Digital Conductivity meter PW 9527 with a Philips PW 9550/60 electrode was used. − The UV absorption spectra were recorded with a Perkin-Elmer Lambda 18 spectrophotometer.

Synthesis: 2,4-Dihydroxy-4′-nitroazobenzene (**1a**) was prepared by reaction of the diazonium salt of 4-nitroaniline with resorcinol.[23]

4-(12-Bromododecyloxy)-2-hydroxy-4′-nitroazobenzene (1b): A mixture of 6.45 g (25 mmol) of 2,4-dihydroxy-4′-nitroazobenzene, 16.4 g (50 mmol) of 1,12-dibromododecane, and 50 mmol of K_2CO_3 in 100 mL of 2-butanone was refluxed for 2 h. The salt was removed by filtration and the filtrate was concentrated by evaporation of the solvent. The product was purified by column chromatography on silica gel with petroleum ether (bp. 40−60°C)/CH_2Cl_2 (1:1, v/v) as eluent. Yield 1.27 g (10%). − ^1H NMR ($CDCl_3$, TMS): $\delta = 1.40$ (m, 16 H, $-[CH_2]_8-$), 1.80 (m, 4 H, $Br-CH_2-CH_2-$, $RO-CH_2-CH_2-$), 3.40 (t, 2 H, $Br-CH_2-$), 4.00 (t, 2 H, $RO-CH_2-$), 6.36−8.30 (m, 7 H, Ar−H), 12.43 (s, 1 H, HO−Ar).

Trimethylammonium{12-[4′-(4′′-nitrophenyl)azo-3′-hydroxyphenyloxy]dodecyl} Bromide (1): A solution of 405 mg (0.8 mmol) of **1b** in 6 mL of a 20% (w/w) solution of trimethylamine in ethanol was heated at 100°C for 1 h in a closed reaction vessel. The mixture was allowed to cool to room temperature and was then thoroughly cooled on ice. The precipitate was collected by filtration and washed with diethyl ether. The product was purified by column chromatography on aluminum oxide (activity grade III) with CH_2Cl_2/MeOH (100:3, v/v) as eluent. Yield 362 mg (80%). Mp. 198°C. − ^1H NMR ($CDCl_3$, TMS): $\delta = 1.40$ (m, 16 H, $-[CH_2]_8-$), 1.80 (m, 4 H, $N-CH_2-CH_2-$, $RO-CH_2-CH_2-$), 3.40 [m, 11 H, $N(CH_3)_3$, $-CH_2-N$], 4.00 (t, 2 H, $RO-CH_2-$), 6.30−8.50 (m, 7 H, Ar−H), 12.43 (s, 1 H, HO−Ar). − $C_{27}H_{41}BrN_4O_4$ (565.55): calcd. C 57.34, H 7.31, N 9.91; found C 57.91, H 7.61, N 9.91.

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[1] D. D. Lasic, D. Papahadjopoulos, *Science* **1995**, *267*, 1275−1276.

[2] D. D. Lasic, F. J. Martin, A. Gabizon, S. K. Huang, D. Papahadjopoulos, *Biochim. Biophys. Acta* **1991**, *1070*, 187−192.

[3] D. D. Lasic, *Angew. Chem.* **1994**, *106*, 1765−1779.

[4] J. G. J. Weijnen, A. Koudijs, J. F. J. Engbersen, *J. Chem. Soc., Perkin Trans. 2* **1991**, 1121−1126.

[5] J. G. J. Weijnen, A. Koudijs, G. A. Schellekens, J. F. J. Engbersen, *J. Chem. Soc., Perkin Trans. 2* **1992**, 829−834.

[6] J. G. J. Weijnen, A. Koudijs, J. F. J. Engbersen, *J. Mol. Catal.* **1992**, *73*, L5−L9.

[7] F. M. Menger, *Angew. Chem.* **1991**, *103*, 1104−1118; *Angew. Chem. Int. Ed. Engl.* **1991**, *30*, 1086.

[8] J. H. Van Zanten, D. S. W. Chang, I. Stanish, H. G. Monbouquette, *J. Membr. Sci.* **1995**, *99*, 49−56.

[9] M. Hebrant, A. Bouraine, C. Tondre, A. Brembilla, P. Lochon, *Langmuir* **1994**, *10*, 3994−4000.

[10] M. Hebrant, P. Tecilla, P. Scrimin, C. Tondre, *Langmuir* **1997**, *13*, 5539−5543.

[11] J. H. Van Esch, A. L. H. Stols, R. J. M. Nolte, *J. Chem. Soc., Chem Commun.* **1990**, 1658−1660.

[12] J. Suh, K. J. Lee, G. Bae, O. Kwon, S. Oh, *Langmuir* **1995**, *11*, 2626−2632.

[13] N. A. J. M. Sommerdijk, M. H. L. Lambermon, M. C. Feiters, R. J. M. Nolte, B. Zwanenburg, *J. Chem. Soc., Chem. Commun.* **1997**, 455−456.

[14] X. Lu, Z. Zhang, Y. Liang, *Langmuir* **1997**, *13*, 533−538.

[15] M. Shimomura, T. Kunitake, *J. Am. Chem. Soc.* **1982**, *104*, 1757−1759.

[16] A. Singh, L. Tsao, M. Markowitz, B. P. Gaber, *Langmuir* **1992**, *8*, 1570−1577.

[17] M. Kasha, H. R. Rawls, M. Ashraf El-Bayoumi, *Pure Appl. Chem.* **1965**, *11*, 371−390.

[18] [18a] M. Shimomura, S. Aiba, N. Tajima, N. Inoue, K. Okuyama, *Langmuir* **1995**, *11*, 969−976. − [18b] F. A. Cotton, G. Wilkinson, P. L. Gaus, *Basic Inorganic Chemistry*, John Wiley & Sons, Singapore, **1987**, p. 470.

[19] P. F. Gordon, P. Gregory, *Organic Chemistry in Colour*, Springer-Verlag, Berlin, **1987**, p. 116−121.

[20] E. W. Kaler, A. Kamalakara Muthry, B. E. Rodriguez, J. A. N. Zasadzinski, *Science* **1989**, *245*, 1371−1374.

[21] K. L. Herrington, E. W. Kaler, D. D. Miller, J. A. Zasadzinsky, S. Chiruvolu, *J. Phys. Chem.* **1993**, *97*, 13792−13802.

[22] M. D. Everaars, A. T. M. Marcelis, A. J. Kuijpers, E. Laverdure, J. Koronova, A. Koudijs, E. J. R. Sudhölter, *Langmuir* **1995**, *11*, 3705−3711.

[23] A. I. Vogel, *Textbook of Practical Organic Chemistry*, Longman Scientific & Technical, Harlow, **1989**, p. 949.

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