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Self-Assembly

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Classical Amphiphilic Behavior of Nonclassical Amphiphiles: A Comparison of Metallacarborane Self-Assembly with SDS Micellization

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Abstract: *The self-assembly of metallacarboranes, a peculiar family of compounds exhibiting surface activity and resembling molecular-scale Pickering stabilizers, has been investigated by comparison to the micellization of sodium dodecylsulfate (SDS). These studies have shown that molecules without classical amphiphilic topology but with an inherent amphiphilic nature can behave similarly to classical surfactants. As shown by NMR techniques, the self-assembly of both metallacarboranes and SDS obey a closed association model. However, the aggregation of metallacarboranes is found to be enthalpy-driven, which is very unusual for classical surfactants. Possible explanations of this fact are outlined.*

Metallacarboranes, such as the $[3,3'\text{-Co}(C_2B_9H_{11})_2]^-$ anion $[\text{CoD}]^-$ (also known as the $[\text{COSAN}]^-$ anion; Figure 1 A), are boron cluster compounds containing metal cations (for example, Co, Ni, and Fe) sandwiched by two dicarbollide clusters.[1] Thanks to their unique properties,[2–4] they have been employed, for example, in radioactive ion extraction[5] and also in biomedical, application-oriented research.[6–9] As a result of the presence of hydridic B−H vertices and charge delocalization, the $[\text{CoD}]^-$ anion exhibits surface activity[10–12] and has an amphiphilic character. As a result, it accumulates at interfaces and is soluble in both oil and water.[13] With this in mind, it is not surprising that metallacarboranes self-assemble in water in spite of their unusual molecular structure.[14–21]

In this Communication, we compare the association behavior of Na[CoD] with the most studied ionic surfactant—sodium dodecylsulfate (SDS; Figure 1 B). Unlike Na[CoD], the molecule of SDS has classical amphilphilic topology, consisting of a long aliphatic tail and a small, charged head group. The closed association model describes the solution behavior of such compounds.[22,23] Our aim is to show that even molecules with an unusual molecular structure can follow the rules established for classical surfactants. Furthermore, unusual and unexpected features of metallacarboranes in solution will be outlined and explained.

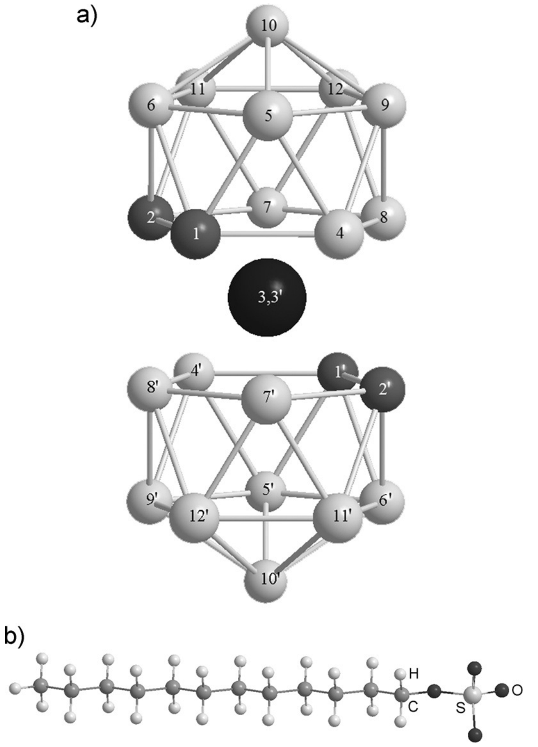

Figure 1. The structures of anions of a) $\text{Na}[3,3'\text{-Co}(C_2B_9H_{11})_2]$ (Na[CoD]) and b) sodium dodecylsulfate (SDS). Cluster-vertex color coding in (a): B−H = light gray, C−H = dark gray, Co = black. Numbering in (a) denotes the numbering scheme for the vertices of the carborane cluster.

Direct proof that Na[CoD] can be included in a broader family of surfactants is shown in Figure 2. Both curves exhibit two breaks in the semilogarithmic plot.[24–26] The curve at lower concentration indicates the point at which the compound starts to accumulate at the interface. It is assigned to $1/K_{\text{aw}}$ (where K_{aw} is the air–water partition coefficient), which is a measure of hydrophobicity. Thus, SDS is more hydrophobic than Na[CoD]. The second break is usually attributed to the critical aggregation (micelle) concentration (denoted CAC or CMC), assuming that the formation of micelles does not cause a further decrease of the γ value.

It is useful to compare the slopes of the two γ versus $\ln(c)$ curves, as the slope is proportional to the surface excess Γ. This is shown in Figure S1 in the Supporting Information and the value of the surface area per molecule (A_S) is calculated. It is evident that Na[CoD] accumulates to a lesser extent than

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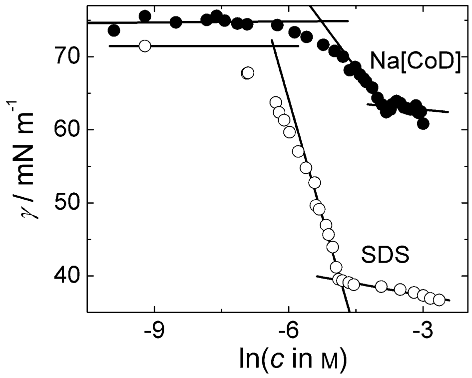

Figure 2. Surface tension (γ) of Na[CoD] and SDS aqueous solutions as a function of ln(c). Data for SDS taken from the literature.[24,25]

SDS at the interface. Furthermore, the Na[CoD] adsorption is a continuous process without an abrupt formation of compact monolayers or "2D aggregates". This continuous adsorption process is demonstrated by the fact that the area occupied by one molecule decreases continuously (with increasing concentration) from a relatively large value (4–5 nm^2) to a limiting value of A_S(Na[CoD]) = 0.98 nm^2, which indicates a preferential parallel orientation of the cluster axis to the plane of the interface[11] (a main axis of length 1.1 nm and a semiaxis of length 0.6 nm in [CoD]$^-$).

With the help of earlier data,[10,11] the molecular picture of Na[CoD] at the interface can be interpreted as follows: While aliphatic tails of SDS are exposed to air forming a fairly compact monolayer (the A_S(SDS) value essentially does not change with c), bulky [CoD]$^-$ are concentrated on the aqueous side of the interface.[10] The clusters slightly repel each other without forming regular monolayers.[11] Cations play a substantial role here, because their hydration energy stabilizes the clusters at the interface.[11]

Considering the fairly low surface activity and the bulkiness of the clusters, we can argue that metallacarboranes should be taken as molecular-scale Pickering stabilizers[27] rather than surfactants (see their ability to stabilize nanobubbles reported below). Nevertheless, it will be shown that Na[CoD] does self-assemble in pure water in a very similar manner to classical surfactants, whereas Pickering stabilizers generally cannot do so.

In our first paper investigating the aggregation of metallacarboranes in 2006, the principle method employed was a light scattering technique.[14] Later on, we realized that NMR spectroscopy was a more suitable tool for studying intermolecular interactions and thermal motions of metallacarboranes.[28] Concentration-dependent ^{1}H {^{11}B} NMR spectra of Na[CoD] over a concentration range of 0.25–200 mM are shown in Figure S2. Significant shifts of resonance signals are evident around the CAC value. The most pronounced changes are observed for the CH1,2 and BH6 signals (Figure 3 a; see Figure 1 a for molecular labelling), revealing the strong influence of mutual interactions in this area of the clusters. Similar but substantially weaker trends were observed for the α-CH$_2$ groups of SDS around the CMC (Figure 3 b).[28,29]

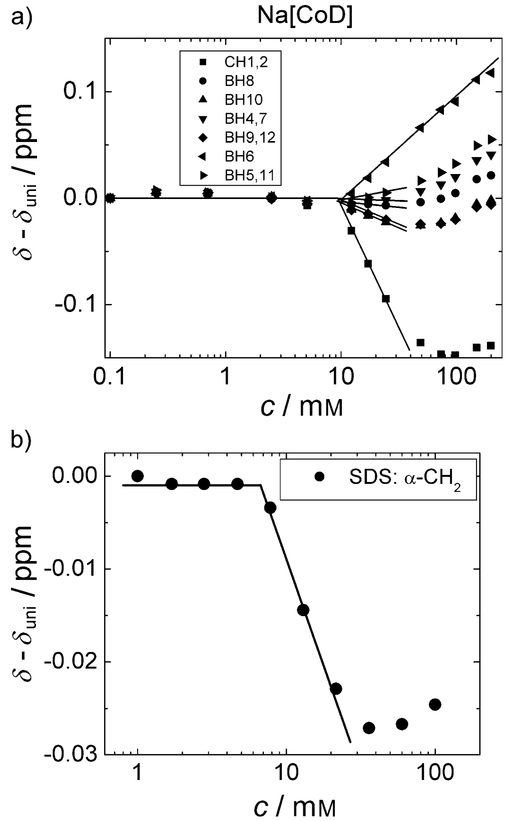

Figure 3. Changes in the relative chemical shifts for signals in a) the ^{1}H {^{11}B} NMR spectra of Na[CoD] and b) the ^{1}H NMR spectra of SDS as a function of concentration at 25 °C. Chemical shift changes for a) specific CH and BH moieties of Na[CoD] (see Figure 1 for numbering scheme) and b) α-CH$_2$ of SDS (taken from the literature)[28] are recorded. Each data point is referenced to the chemical shift of the unimer (δ_{uni}) for the highest dilution of compounds, that is, where only unimers appear.

The similarities between the solution behaviors of SDS and Na[CoD] run even deeper. We carried out DOSY ^{1}H NMR experiments to detect thermal self-diffusion of [CoD]$^-$. The results for Na[CoD] and SDS diffusion are compared in Figure 4, where experimental points were fitted according to the model of closed association (a simple mathematical model and the results of the fitting procedure are shown in the NMR section of the Supporting Information). The fitted data unambiguously indicate that self-assembly of both surfactants can be satisfactorily described by the same model.[22,23]

Despite a similar size and mechanism of formation, the structure of the metallacarborane associates is hardly comparable to a classical micelle with a hydrophobic core and a charged layer at the micellar surface. Small-angle X-ray scattering (SAXS) data show that the aggregation number of Na[CoD] is very low ($N^{agg} = 5$) as compared to SDS ($N^{agg} = 62$). Furthermore, the average distance between centers of gravity of neighboring clusters within aggregates 0.59 nm (calculated from correlation peaks in SAXS curves) indicates that a parallel orientation of [CoD]$^-$ (a semiaxis of length 0.6 nm) is preferred.

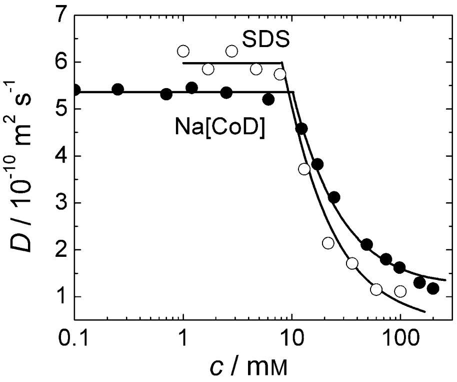

Figure 4. Diffusion coefficients (*D*) obtained from ^{1}H DOSY NMR experiments at 25 °C for the CH1,2 signals of Na[CoD] plotted as a function of concentration. The corresponding diffusion coefficients for the α-CH_2 resonance signals of SDS were obtained from previous reports.[28] Data fitted by the closed association model (see Equations [2 and 3] in the Supporting Information).

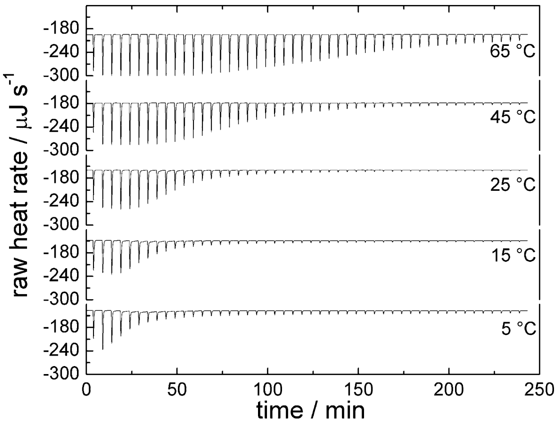

Figure 5. Raw ITC data for the deaggregation process during the titration of Na[CoD] (120 mM) into pure water at various temperatures.

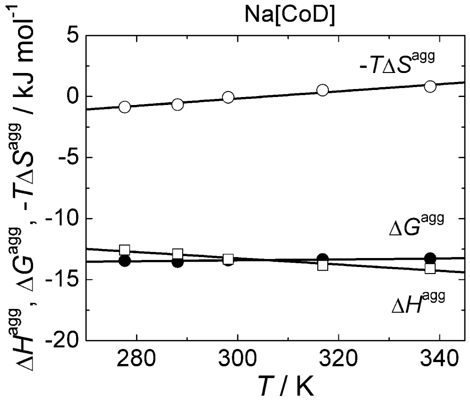

Figure 6. Thermodynamic parameters (ΔG^{agg}, ΔH^{agg}, and $-T\Delta S^{agg}$) of Na[CoD].

Plots of both the CAC values for Na[CoD] and the CMC values for SDS against temperature (see Figure S3) have a classical shape.[30,31] The temperature dependence of the CAC is useful to calculate the free energy of aggregation. Thermodynamic parameters like the free energy, enthalpy, and entropy of aggregation (ΔG^{agg}, ΔH^{agg}, and ΔS^{agg}, respectively) allow us to better understand the mechanism of the self-assembly process. An important parameter to evaluate the ΔG^{agg} value is the degree of counterion binding to micelles (β). The β value is almost zero for Na[CoD], but rises to around 80 % for SDS micelles.[31] For more details, see the thermodynamics section in the Supporting Information.

To complete a thermodynamic description of the self-assembly of Na[CoD], a method for the direct determination of the ΔH^{agg} values is needed. With this in mind, isothermal temperature calorimetry (ITC) experiments were run at various temperatures, where a concentrated Na[CoD] solution was slowly titrated into pure water.[32,33] The aggregates were decomposed into $[CoD]^-$ unimers and the measured process corresponded to deaggregation. The raw data is shown in Figure 5. ITC is an exceptionally sensitive method that detects mutual interactions and the redistribution of nanostructures.[34] The presence of single, sharp endothermic peaks in Figure 5 proves that "micelle" deaggregation is the only process occurring during Na[CoD] dilution. Considering the data, it is found that the ΔH^{agg} value only slightly depends on temperature and is exothermic (around $-13\,kJ\,mol^{-1}$).

From the free energy and enthalpy of aggregation we calculated also the ΔS^{agg} value. All the thermodynamic parameters for Na[CoD] and SDS micellization are shown in Figure 6 and Figure S4, respectively. In both cases, the ΔG^{agg} value is negative and almost independent of temperature. Both enthalpy and entropy terms are usually dependent on temperature (see Figure S4), and compensate each other as demonstrated in the so-called compensation plot[35] (see Figure S5 and further comments in the Supporting Information).

The micellization of classical hydrocarbon and fluorocarbon surfactants is typically explained as an entropy-driven process (see Figure S4 for SDS) since the driving force is the classical hydrophobic effect, resulting from gains in entropy caused by the release of solvent molecules.[36,37] This is not the case for Na[CoD], for which the entropy contribution is, in fact, negligible (Figure 6), pointing to a nonclassical hydrophobic effect.[38,39] An explanation for the dominant role of the enthalpy term is not straightforward (see the Supporting Information for comments). Even though the model for the B−H⋯H−C dihydrogen bond[40] sounds attractive (it is consistent with a parallel orientation of clusters within the aggregates (see SAXS results), and with the NMR spectral changes in Figure 2 A), such a bond has not yet been directly proven in metallacarborane solutions. Considering the current state of knowledge, we prefer an explanation based on a nonspecific hydrophobic action[36–39] with a predominant role for (de)hydration of the cluster (see the sections on compensation plots and enthalpy-driven association in the Supporting Information).

Finally, the above-described Na[CoD] associates are compared with large spherical nanoparticles. These large nanoparticles were first detected using light-scattering (LS) techniques in our laboratory in 2006[14] and were subsequently interpreted as monolayer vesicles in 2011 and subsequent years.[17,18,41] Spherical nanoparticles are sufficiently large for LS, but they are beyond the detection limit of DOSY experiments. The DOSY technique is, however, suitable for detection of low-molar-mass molecules in complex mixtures, which do not scatter light.

It was recently reported for solutions of surface-active polymers that a "slow mode" (that is, large particles) could be detected even for non-associating compounds by LS.[42] This result was interpreted as the stabilization of nanobubbles by the surfactant. Thus, the surface-active $[CoD]^-$ clusters would be packed at the surface of nanobubbles[12] in the same way that they are located in vesicles, according to the model proposed by Bauduin et al.,[12,17] making them almost indistinguishable by scattering techniques. In our current LS study (see the results in Figure S6 in the Supporting Information with further comments), we confirmed the presence of single molecules, small micelle-like aggregates, and spherical nanoparticles in solution. The fraction of large particles is, however, very low (less than 1%; see the cryoTEM analysis in Figure S7), and it is significantly less than what we claimed in 2006.[14] Their inner structure is still unclear, since the cryoTEM image in Figure S7 is hardly comparable to that of true vesicles with an interior area of lighter density.[41] We also observed a non-negligible fraction of nanobubbles by LS, which are most likely stabilized by Na[CoD]. This supports the above-mentioned theory that metallacarboranes should be taken not only as surfactants, but also as molecular-scale Pickering stabilizers.[27]

In summary, it is evident that a metallacarborane cluster, despite its peculiar shape and structure, behaves like a classical surfactant in many cases. The formation of more complex structures like lamellae, vesicles, or worm-like particles can also be detected for Na[CoD] as well as for SDS.[43] Furthermore, both compounds can form complexes with cationic polyelectrolytes and also with electroneutral poly(ethylene oxide) (PEO), as previously described.[44,45] The main differences between behavior of Na[CoD] and SDS were found in the thermodynamics of their self-assembly in water.

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