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Cationic Shape-Persistent Macrocycles: The Unexpected Formation of a Nano-Size Supramolecular Dimer

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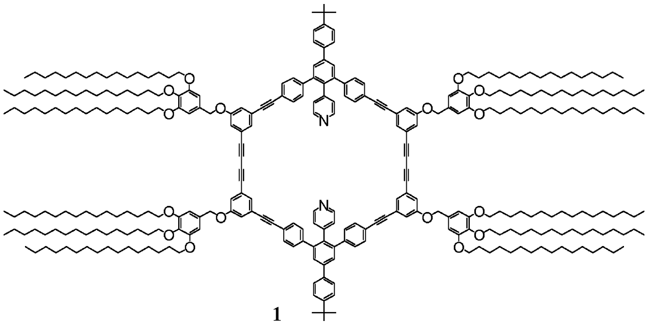
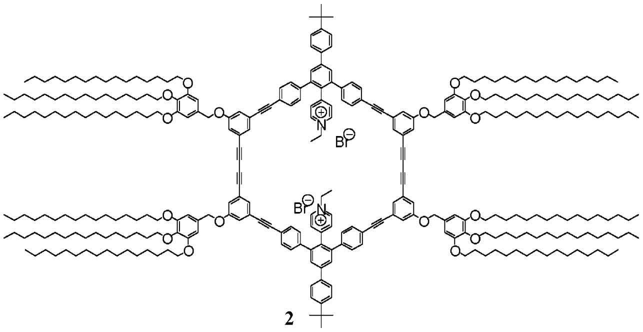
The supramolecular organization of shape-persistent macrocycles in one, two, or three dimensions has recently become a topic of great interest.[1] Apart from infinite aggregates, the formation of well-defined finite-size assemblies from mesoscale building blocks is currently an attractive goal in supramolecular chemistry.[2] For example, a dimerization has been observed for hemi-alkylated cyclopeptides or for macrocycles with chiral helicene units in the backbone.[3−5] Furthermore, nanoscale supramolecular objects are formed by metal-supported self-assembly of rigid rings containing exotopic binding sites.[6] One of our aims during the last years dealt with the 1D organization of shape-persistent macrocycles by solvophobic interactions. We could show that rigid macrocycles that are decorated with oligo-alkyl side chains at their periphery aggregate in solvent mixtures that contain a nonsolvent for the rigid core.[7] However, only a weak association could be observed due to the restricted compound solubility that did not allow an increase of the association constants by further decreasing the solvent polarity. One way to overcome the solubility problem is to attach polystyrene oligomers to the rigid backbone. The coil−ring−coil block copolymers are well soluble in cyclohexane at slightly elevated temperatures.[8] Below about 35 °C, they aggregate into supramolecular hollow cylindrical brushes.

Alternatively, the solubility can be increased by variation of the backbone of the macrocycles. It might be possible that parts of the macrocycle that are not in plane with the rigid ring backbone (for steric reasons) increase the solubility and at the same time maybe support, but at least not hinder, the aggregation. Since a 1,2,3-substitution pattern does not allow all phenyl rings to lie in one plane, we intended to investigate the solubility behavior of such macrocycles (such as **1**) if they are decorated with extraannular oligo-alkyl chains.[9]



1

1 is well soluble in chlorinated solvents, aromatic solvents, THF, and also cyclohexane, as we speculated at the beginning of our work. A broadening of the signals in the ^{1}H NMR spectrum in cyclohexane was a first hint of an aggregation of the molecules (see Supporting Information). The aggregate formation was further investigated by dynamic light scattering (DLS) measurements. The distribution of relaxation times in the autocorrelation function was obtained by CONTIN analysis.[10] It contains two maxima, one at a hydrodynamic radius of approximately 2 nm, which corresponds to the macrocycle **1**, the other at approximately 50 nm (Figure 1a). The fraction of the larger species in solution increases with higher concentration. We assume that the larger objects are a mixture of tubular aggregates of different length which are formed to minimize the contact area between the aromatic core of the macrocycles and the cyclohexane, as it is observed for the coil−ring−coil block copolymers.[8] However, for **1**, the relative peak intensities in the CONTIN fit clearly show that the aggregates are only a minor fraction of the solute. To enforce the aggregation the (intraannular) pyridyl groups of the macrocycle were alkylated by treating **1** with ethylbromide.[11] **2** is well soluble in chlorinated solvents, THF, and even in cyclohexane.



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While the ^{1}H NMR spectrum in dichloromethane is well resolved, the spectrum in cyclohexane is again broadened (see Supporting Information). This observation, together with the structure of **2**, indicated an aggregation of these amphiphiles into extended tubular aggregates that avoid a contact of the ionic parts of the molecule with the cyclohexane. However, contrary to what we expected for these proposed aggregates, even at a concentration of 2 wt %, the solution is neither highly viscous nor does it exhibit any birefringence, as it is found for cyclohexane solutions of the coil−ring−coil block copolymers. DLS measurements (1.4 wt %) gave an unexpected result (Figure 1a). The CONTIN fit shows now only one maximum that corresponds to a hydrodynamic radius (R_H) of approximately 3−4 nm, and no larger aggregates could be detected. Small-angle X-ray scattering experiments (SAXS) in cyclohexane support that result, showing only particles with a small radius of gyration (R_G) of 1.75 nm (as expected smaller than R_H) at all concentrations (see Supporting Information). Moreover, the ob-

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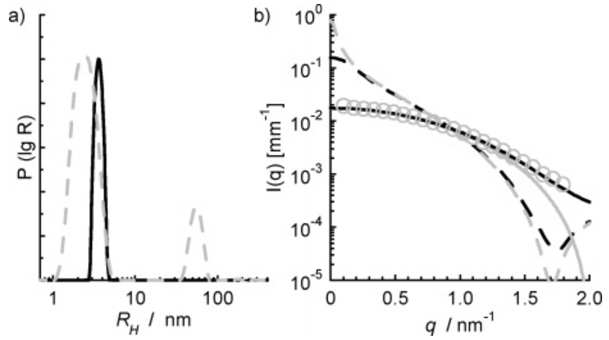

Figure 1. (a) CONTIN fit of DLS-derived distribution of **1** in cyclohexane (1.5 wt %, dashed gray line) and of **2** in cyclohexane (1.4 wt %, solid line). (b) Experimental scattering intensity of **2** in cyclohexane (○) compared to theoretical scattering of different models: (*dashed black line*) tube due to the packing of 20 macrocycles; (*dashed gray line*) tube due to the packing of 100 macrocycles; (*gray line*) sphere (2.2 nm) (for a scattering vector $q < 1.0$ nm^{-1} the curve superimposes with the scattering curve of the disk); (*black line*) disk with a diameter of 4.5 nm and a height of 2.35 nm.

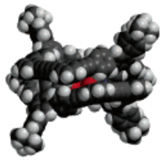

Figure 2. Proposed structure of the supramolecular dimer (only the rigid backbone of the rings is displayed): the extraannular *p*-(*tert*-butyl)phenyl groups block the top and bottom of the dimer and prevent an aggregation of the supermolecules.

served scattering data (○) can be clearly distinguished from spheres and tubular objects of different length. The observed data correspond well to the calculated scattering profile of a disk with a diameter of 4.5 nm and a height of 2.35 nm. By assuming a compound density of 1.14 g/cm^3,[12] the molecular weight of the scattering object is calculated to be 10 000 g/mol.

The results of the X-ray scattering experiments and DLS experiments undoubtedly show that the quarternization of the slightly aggregating macrocycles **1** does not lead to the formation of extended tubular structures in the nonpolar solvent, as it is was expected. Rather, the DLS and X-ray scattering experiments indicate the presence of well-defined dimers of the amphiphile **2** in the cyclohexane solution. This is also confirmed by the size of the disk described above. A simple computer model of **2** (stiff cycle, random walk side chains) gives an idea of the size of one macrocycle: Its scattering can be described by a disk with a diameter of 4.3 nm and a thickness of 1.1 nm, that is, half the disk thickness that was extracted from the experimental scattering data. It should be noted that within the investigated concentration regime (0.005−1.4 wt %) no large aggregates could be detected, but dimerization occurs completely even at the lowest concentration.

Although on first glance an infinite aggregation should be preferred to shield the charged parts of the macrocycle from the nonpolar cyclohexane environment, the exclusive dimer formation can be explained with a boat conformation of the macrocycles in which the pyridinium groups point into the dimer center that accommodates the four bromide ions (Figure 2).[13]

The proposed structure resembles sandwich-type complexes of crown ethers or inclusion complexes of calixarenes.[14] As pointed out before, well-defined aggregates of shape-persistent macrocycles are only scarcely observed.[3−5] In the cases reported before, the structure and functionality of the single macrocycle determines the preference of dimerization over infinite aggregation. In the example described here, the macrocycle is in principle capable of forming extended aggregates (as it is observed for **1**). However, the ion-triggered aggregation process induces a conformational locking of the macrocycles in the boat conformation that self-blocks the top and bottom of the dimer, hindering a further aggregation after the dimerization. As far as we know, this behavior has not been described before for shape-persistent macrocycles.

In summary, we have shown by detailed DLS and X-ray scattering experiments that nanometer-size dicationic shape-persistent macrocycles in nonpolar solvents do not form infinite tubular aggregates, as might be expected from their chemical structure, but dimerize to defined supermolecules. The exclusive dimerization is not programmed by synthetic efforts but is a result of the ability of the macrocycles to adopt during the aggregation a self-complementary shape that blocks the top and bottom of the supermolecule, thus preventing a further aggregation. It has to be marked that dimerization occurs even at the lowest investigated concentration. Currently, we are investigating the concentration and counterion dependence of the aggregation process further as well as the behavior of this and other charged macrocycles in different environments.

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Supporting Information Available: Synthesis and characterization of all new compounds as well as information about the X-ray scattering experiments. This material is available free of charge via the Internet at http://pubs.acs.org.

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