5900 *Macromolecules* **2009**, *42*, 5900–5902
DOI: 10.1021/ma901022w

Macromolecules
NOTE

Temperature-Induced Switching between Aggregated and Nonaggregated States in Coil−Ring−Coil Block Copolymers

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Received May 11, 2009; Revised Manuscript Received June 30, 2009

The formation of hollow cylindrical aggregates by organization of appropriate macrocycles has attracted considerable interest during the past several years.[1] In terms of possible applications in nanotechnology or as sensors, it is necessary to understand the molecular requirements that lead to aggregation.[2] It is generally accepted that on one hand electron-deficient macrocycles show a higher aggregation tendency than electron neutral or even electron-rich compounds and that bulky substituents at the periphery of the molecules hinder the aggregation. Solvents play a crucial role in aggregation, and solvophobic interactions can induce aggregation and fiber formation even when the aforementioned criteria are not fulfilled. Up to now, the aggregation of shape-persistent macrocycles in solution has mostly been investigated by means of NMR spectroscopy, vapor pressure osmometry, or dynamic light scattering. While the aggregation constants are reported for several of the compounds, the average number of molecules participating in the aggregates has not been investigated in detail. In addition, only little knowledge exists on the structure of the aggregates in solution.[3]

Our recent work was focused on large shape-persistent macrocycles with an internal diameter above 1 nm and peripheral solubilizing side groups.[4] We demonstrated that the aggregation tendency of macrocycles with two oligostyrene side groups (coil−ring−coil triblock copolymers) can be tuned by the size of the styrene block. For example, **1** dissolves well in warm cyclohexane and upon cooling to room temperature rapidly forms a viscous solution that is strongly birefringent (polarizing microscopy). Initial light- and X-ray scattering experiments in solution indicated the formation of extended supramolecular hollow cylindrical polymer brushes that obtain a lamellar morphology in the solid state. In addition, aggregates of **1** when rapidly cast from solution can be visualized by electron microscopy (EM) and atomic force microscopy (AFM). These investigations show tubular aggregates and bundles of these aggregates. Up to now, no detailed information is available on the structure in solution.

In this report we describe a detailed small-angle X-ray scattering investigation (SAXS intensity $I(q)$; $q = 4\pi \sin(\Theta/2)/\lambda$) of the solution structure of **1** and aggregates of **1** as well as the temperature dependence of the aggregation process.

First, we analyzed the scattering of **1** ($c = 4.63$ g/L) in cyclohexane at 45 °C (Figure 2). From the absolute forward scattering intensitiy $I(q=0) = 0.0033\ \mathrm{mm}^{-1}$ the molecular weight of the particle in solution was obtained as 6900 g/mol, which corresponds well with the theoretical molecular weight of 6946 g/mol if the macrocycles are not aggregated. The q dependence of the scattering intensity was theoretically modeled by a stiff macrocycle with freely rotating phenyl groups and side chains described by a self-avoiding walk of freely rotating chains (Supporting Information). Averaging this model over 500 conformations delivers the final scattering intensity.

When the solution of **1** in cyclohexane is cooled below 40 °C, the formation of aggregates can be observed by an increase of the solution viscosity. However, in order to ensure equilibrium conditions at the beginning of the measurements, the sample was stored at room temperature for 7 days. The temperature was then stepwise raised. Measurement time was in each case only 1 s to ensure sufficient time resolution. The first measurement at each temperature was performed 3 min after the temperature jump, and measurements were repeated every 2 min until no change in the scattering intensity could be observed. On average, the sample was held for about 25 min on each temperature, except the highest temperature where we used only 5 min due to technical reasons.

The scattering intensity of the whole series of measurements can be described by a single model shown by the solid lines in Figure 3 and discussed in detail in the Supporting Information. Each scattering curve is described by a mixture of free molecules with a scattering intensity as shown in Figure 2 and extremely large cylindrical aggregates of the macrocycles with a constant length of 400 nm. The only parameter changing as a function of temperature is the amount of aggregated molecules; the total number of molecules is fixed.

The actual length of the cylinders could not be determined by small-angle X-ray scattering. Even with the excellent q range achieved in this experiment ($q_{\mathrm{min}} = 0.018\ \mathrm{nm}^{-1}$) cylinders with a length greater than 200 nm cannot be distinguished (Supporting Information). Therefore, we assumed a length of 400 nm as observed by dynamic light scattering under the assumption of a rodlike object structure.[4b]

The electron density profile of the cross section of the cylindrical aggregates is shown in the inset of Figure 3. It is similar, but not equal, to the one of a single molecule. The sharp increase inside the tube and the extension to a greater radial distance at the outside reflect the fact that the side chains in a cylindrical aggregate cannot penetrate anymore in the inner region of the macrocycle and therefore need to be stretched more to the outside of the macrocycles. Since absolute intensities have been obtained, the electron density of the cross section can be evaluated quantitatively. The scattering data suggest a packing density of

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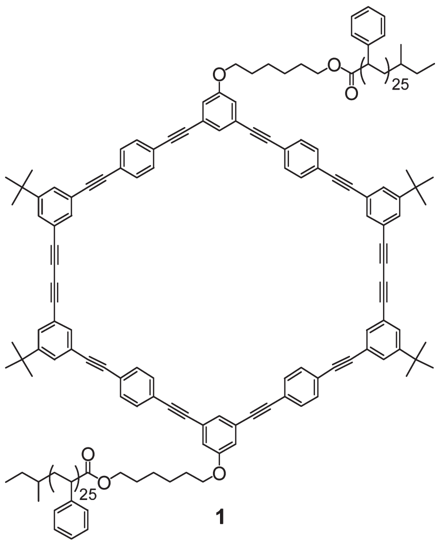
2.9 macrocycles per nm cylinder length, a radius of the cross section of $R_C = 4.6$ nm, and a maximum extension of the profile up to 10.5 nm. The comparison of this result with the dimensions of **1** given from chemistry (maximum extension of 8.55 nm assuming fully stretched chains)[5] and the calculated distance of 0.34 nm between two macrocycles within a tube shows that a single aggregated cylinder of macrocycles is not compatible with the scattering data.

The previous discussion has shown that a plausible solution is the assumption that the equilibrium in solution exists not only between free macrocycles and macrocycles in the cylindrical aggregate (free cylinders) but also between free cylinders and aggregates of the cylinders themselves. As a consequence of such a complicated model with many parameters, it is not possible to determine the macrocycle distance from the scattering data. By assuming a ring-to-ring distance of 0.6 nm within a tube,[6] it is possible to describe the experimental scattering intensity by a mixture of aggregates in solution that contains about 60 wt % free cylinders, 27 wt % cylinder dimers, and 13 wt % cylinder trimers (Supporting Information).[7] It has to be noted that AFM and EM investigations of solid samples of **1** prepared under nonequilibrium conditions have already shown single tubular aggregates as well as dimers and trimers.[4b] However, until now it was not clear if these observations reflect the situation in solution of if they are a result of the sample preparation. The detailed investigations described here unambiguously show that at the concentrations investigated here the assumption of a monomer–cylinder equilibrium is not sufficient to be taken into account and the formation of higher aggregates cannot be ignored.



1

Figure 1. Chemical structure of **1**.

Opposite to structures containing extended π-systems or polar side groups that facilitate the aggregation,[8] we ascribe at present the behavior of the ring–coil oligomer to the cylohexane which is at 34 °C θ-solvent for polystyrene. Above the θ-temperature the polymer side chains are in a swollen state. The solvated side chains occupy more space than in its unperturbed state and counterbalances the tendency of macrocycle aggregation. Thus, single molecules result in solution. Lowering the temperature leads to a shrinking of the polymer chains (including solvent); the aggregation of the macrocycles dominates the system, resulting in extremely large tubular aggregates. The high aggregation tendency of the PS–macrocycle–PS oligomers in cyclohexane below θ-temperature indicates that the oligostyrene plays an active role in the aggregation process. In addition, favorable PS–PS interactions can lead to intermolecular association of the oligomers. However, from experiments in other solvents where no aggregation occurs below the θ-temperature of the system (*trans*-decalin, θ-temperature = 20.5–24 °C; methylcyclohexane, θ-temperature = 60–70 °C),[9] we can conclude that the solubility of the side chains is an important, but not the only parameter dominating the aggregation.[10] Although experimentally not proven, we can assume that in solution cyclohexane is included inside the cylinders—a fact that seems quite natural imaging the osmotic pressure of the solvent in the case of a truly hollow cylinder. In addition, also three molecules cyclohexane per macrocycle are present in **1** in the solid state.[4b] Cyclohexane seems to be ideally suited for this purpose, and even minor changes in the solvent size or quality have a profound influence on the aggregation behavior.

The deaggregation of the tubes takes place in a rather narrow temperature range. However, the cylinder length stays high nearly over the entire temperature series (Supporting Information), and the scattering intensity can be described by a model that takes only long aggregates and monomeric rings into account. This behavior shows all characteristics of a cooperative self-assembly.[1e,10,11] It is a consequence of several reinforcing noncovalent interactions, and slight changes in the environment

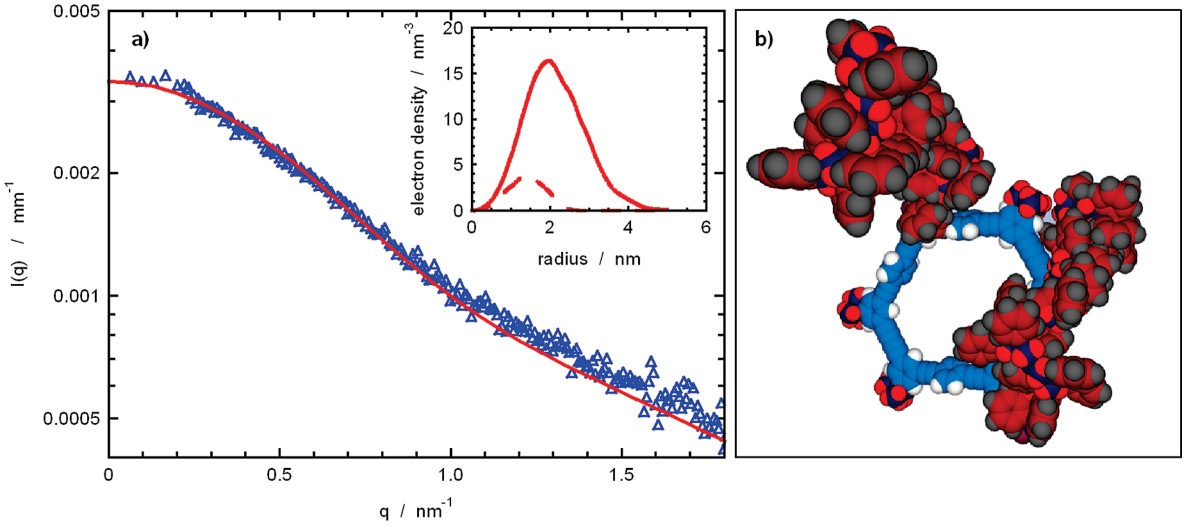


Figure 2. (a) Experimental scattering intensity of **1** in cyclohexane at 45 °C. The inset shows the electron density of the macrocycle (- - -) and the macrocycle including the side chains (—). The solid line represents the average scattering intensity of 500 different conformations of the simulation model. (b) One conformation of the simulation shown as a space-filling model.

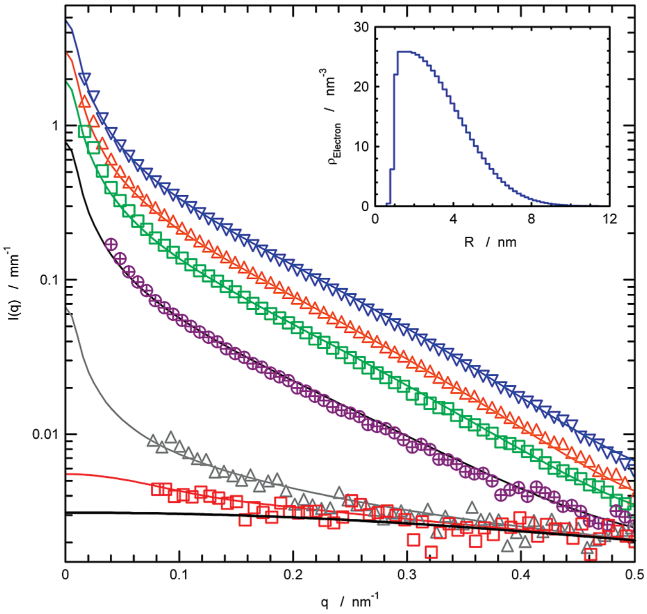


Figure 3. Experimental scattering intensity of compound **1** in cyclohexane at different temperatures. The scattering intensity can be described by big cylindrical aggregates in equilibrium with free single molecules (see solid lines), the amount of aggregated molecules changing with temperature. Starting from top: (blue ▽) 25 °C, 99% aggregates; (pink △) 30 °C, 62% aggregates; (green □) 33 °C, 40% aggregates; (purple ⊕) 36 °C, 16% aggregates; (gray △) 39 °C, 1.3% aggregates; (red □) 45 °C, 0.4% aggregates; (—) free single molecules. The inset shows the radial electron density of the cross section of the cylindrical aggregates.

(e.g., solvent) have a tremendous effect on the overall behavior of the system.

In summary, we have shown by detailed small-angle X-ray scattering experiments the temperature-induced switching between aggregated supramolecular structures and single molecules. In addition to the temperature-dependent behavior, we could also identify the molecular solution at higher temperatures as well as the structure of the aggregates at lower temperatures. Extremely long cylindrical architectures are formed, and only the amount of aggregated macrocycles is changing as a function of temperature while the length of the cylindrical aggregates is remaining high, a typical behavior for a cooperative assembly. Currently, we are investigating the concentration dependence of the aggregation process and the behavior of similar macrocycles in different environments.

Acknowledgment. We thank the DFG for financial support. We gratefully acknowledge beamtime at the beamline ID02 at the ESRF, Grenoble, and helpful assistance and discussions by the responsible beamline operator, T. Narayanan.

Supporting Information Available: Detailed discussion of the temperature-dependent scattering intensities and evaluation of the models. The material is available free of charge via the Internet at http://pubs.acs.org.

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(5) For the macrocycle we have a radius of 1.15 nm and the maximum length of the side chains is 7.5 nm (polystyrene, $n = 25$ and the spacer group yielding totally ∼60 C−C bonds; the maximum side chain length is calculated under the assumption of a fixed valence angle (109°), leading to an effective monomer length of 0.251 nm), resulting in a maximum dimension of 8.6 nm assuming fully stretched oligostyrene chain. One might argue that despite the fact that the sample has a polydispersity below 1.05, there are still oligostyrenes attached to the macrocycles with a longer end-to-end distance.[4c] However, it is rather unlikely that oligomers adopt a fully expanded all-trans configuration to such an extent that the scattering curve could be reasonably described.

(6) The value of 0.6 nm is observed for the macrocycles distance within solid-state aggregates of **1** (cf. ref 4c).

(7) Small changes of the macrocycle distance results in other weight percentage of the aggregates.

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