Communication

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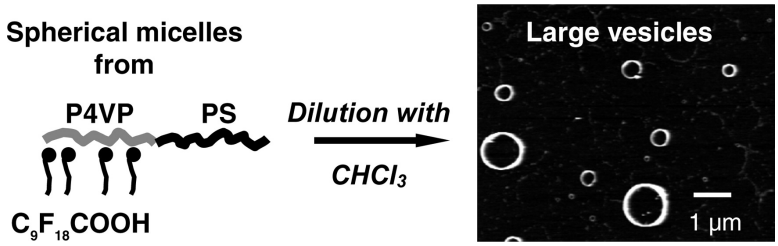
J. Am. Chem. Soc., **2005**, 127 (18), 6526-6527• DOI: 10.1021/ja050053m • Publication Date (Web): 13 April 2005



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Dilution-Induced Spheres-to-Vesicles Morphological Transition in Micelles from Block Copolymer/Surfactant Complexes

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Among the different morphologies that have been obtained thus far for block copolymer micelles, vesicles have received special interest due to their potential applications in numerous fields ranging from cosmetics to anticancer agent.[1] Since polymer molecular weights (MW) are much greater than those of usual vesicle-forming surfactants, the structural features of block copolymer vesicles, as well as properties including stability, fluidity, and intermembrane dynamics, are quite different from those of their low MW analogues and can be tuned by changing the characteristics of the polymer blocks.[2] Block copolymer vesicles have been generally generated in aqueous media from various amphiphilic block copolymers and mixtures of block copolymers.[3] Amphiphilic block copolymers/low MW surfactants complexes have also proven to be useful precursors for the preparation of vesicles. In these systems, one block of the copolymer is complexed by the surfactant through specific noncovalent interactions resulting in the insoluble vesicular layer, while the remaining uncomplexed blocks point out toward the inner and the outer regions of the vesicle.[4] Stimuli-induced morphological transitions have been rarely observed for block copolymer vesicles. An illustration of this concept can, however, be found in block copolymer vesicles sensitive to the solvent composition[5] and in a very recent report in which a microspheres-to-vesicles transition is controlled by diamidopyridine recognition units.[6]

In this communication, we report on a simple approach to trigger a spheres-to-vesicles morphological transition from poly(styrene)-*block*-poly(4-vinylpyridine)/perfluorodecanoic acid complexes (PS-*b*-P4VP/PFDA) in chloroform. These complexes, which form spherical micelles at a concentration of 1 g/L, rearrange into vesicles when the solutions are diluted, as confirmed by combined dynamic light scattering (DLS), atomic force microscopy (AFM), optical microscopy (OM), and transmission electron microscopy (TEM) investigations. Moreover, this morphological transition can be further used as a tool to encapsulate molecules of interest in the interior of block copolymer vesicles.

A PS_{327}-*b*-$P4VP_{27}$ diblock copolymer was prepared by living anionic polymerization (copolymer polydispersity of 1.1, the numbers in subscript refer to the number-average degree of polymerization of each block) and was dissolved in chloroform. PFDA was dissolved in chloroform and then mixed with the copolymer solution under stirring. The final concentration was adjusted to 1 g/L, and the 4VP/PFDA molar ratio was fixed to 1/1. The resulting complex as well as the starting materials were first investigated by DLS, and the intensity autocorrelation function was analyzed by a cumulant expansion leading to the average hydrodynamic diameter (D_h) and the polydispersity index (PDI) of the aggregates,

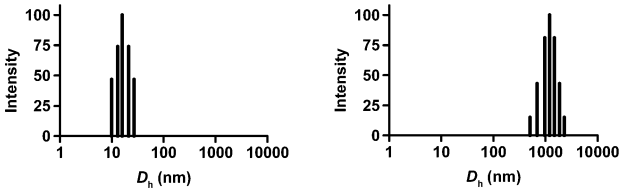

Figure 1. CONTIN size distribution histograms obtained for the PS_{327}-*b*-$P4VP_{27}$/PFDA aggregates with a 1/1 4VP/PFDA molar ratio at a concentration of 1 g/L (left) and after dilution to 0.1 g/L (right).

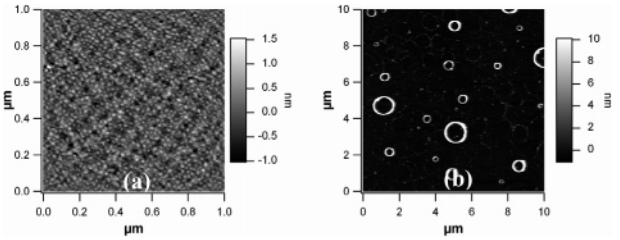

Figure 2. AFM images of aggregates from PS_{327}-*b*-$P4VP_{27}$/PFDA complexes with a 1/1 4VP/PFDA molar ratio at 1 g/L (a) and diluted at a concentration of 0.1 g/L (b).

as defined elsewhere.[7] No aggregated species were detected for both the PS_{327}-*b*-$P4VP_{27}$ copolymer and the PFDA molecules, indicating that these compounds are molecularly dissolved in chloroform for concentrations ranging from 0.01 to 1 g/L. Micellar aggregates with a D_h of 15 ± 1 nm and a PDI of 0.12 were, however, detected for the mixture. However, dilution has a dramatic effect on the D_h and on the PDI of the aggregates, which increased to 1245 ± 218 nm and 0.31, respectively. A typical D_h distribution histogram obtained by a CONTIN transformation[7] of the DLS data is shown in Figure 1 before and after dilution. Obviously, the initial population of micelles has formed much larger structures.

Similar increases in D_h and PDI were noted whenever the initial solution was diluted to other concentrations. This deep change in the characteristic features of the micellar aggregates was irreversible since the slow evaporation of the solvent to the starting concentration could not restore the initial D_h. The direct preparation of the PS_{327}-*b*-$P4VP_{27}$/PFDA complexes at a concentration of 0.1 g/L resulted in the formation of spherical aggregates with a D_h of 16 ± 2 nm, indicating that the dilution step is indeed a prerequisite for the large structures to be observed.

To obtain more information about the structural features of these aggregates in both the initial and diluted states, morphological investigations by AFM were performed. Samples for AFM were prepared by spin-coating solutions onto carbon-coated mica. Figure 2a shows an AFM height image obtained from micellar aggregates prepared at a concentration of 1 g/L. Rather monodisperse spherical

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10.1021/ja050053m CCC: $30.25

micelles have been observed. The mean diameter of the dried micelles has been measured to be 13.7 nm. These spherical micelles are thought to consist of a core formed by P4VP/PFDA hydrogen-bonded complexes surrounded by a PS corona. In addition to hydrogen-bonding between the nitrogen atom of P4VP and the carboxylic acid group of PFDA, additional interactions between the fluorinated tails should also play a role in the aggregation process since no aggregation has been detected for the corresponding PS-*b*-P4VP/decanoic acid complexes in chloroform. An AFM height image has been collected on the micellar solution diluted to 0.1 g/L as shown in Figure 2b. Polydisperse vesicles with diameters of at least 100 nm have been observed. Most of the vesicles are on the micrometer scale and can be observed by optical microscopy (see below).

The effect of the 4VP/PFDA molar ratio and the length of the tail of the perfluorinated surfactant has been studied. Spherical micelles are observed in all cases, although their characteristic size is dependent on these two factors as discussed in the Supporting Information (Figures S1 and S2). Vesicles are again formed whenever these solutions are diluted.

The direct formation of vesicles has been recently reported in mixtures of a PS-*b*-P4VP diblock with perfluorooctanoic acid in chloroform.[8] In contrast to these results, vesicles are not formed in our case. The discrepancy between the present study and these previous results could be accounted for by different molecular characteristics of the used PS-*b*-P4VP copolymers or by a different preparation method for the complexes. In this respect, a high MW, nearly symmetric PS-*b*-P4VP copolymer was used in the previous study while a lower MW, highly asymmetric one is considered here. In the present study, mixtures were prepared under stirring while slow addition of the surfactant to the copolymer and ultrasonic treatment were used in the previous study.[8] The use of this previously reported preparation method was, however, not successful to obtain directly vesicles in the present study.

To the best of our knowledge, dilution-induced micelles-to-vesicles morphological transition has not been reported thus far for block copolymer-based systems. Actually, dilution generally induces vesicles-to-micelles transition in block copolymer micelles.[9] In the present case, the competition between complexation and micellization during sample preparation is believed to be a key factor in controlling the initial morphology. The initial spherical micelles could result from the aggregation of insoluble P4VP/PFDA complexes in which only a part of the available 4VP units would have been complexed to PFDA molecules. Following dilution of the system, partial resolubilization or swelling of the initially formed P4VP/PFDA complexes could occur. Further complexation with remaining fluorinated surfactant molecules could then be observed, leading again to insoluble complexes and aggregation. The increased amount of fluorinated tails in these complexes would nicely explain the spheres-to-vesicles transition.

The simplicity of the approach to trigger the spheres-to-vesicles transition suggests that this methodology can be used for the encapsulation of molecules of interest. In this respect, we have studied the encapsulation of a dye, perylene bisimide, into the vesicles. To achieve this goal, the initial spherical micelles at 1 g/L were diluted by a solution of perylene bisimide in $CHCl_3$. The diluted solution was then dialyzed for 2 h against pure $CHCl_3$ to remove nonencapsulated dyes. Since encapsulated dyes are not prone to permeate through the perfluorinated walls of the vesicles, this procedure resulted in vesicles containing the dyes exclusively inside the vesicles, as shown in Figure 3. This result demonstrates a potential application of the spheres-to-vesicles transition for the microencapsulation or sequestration of targeted molecules.

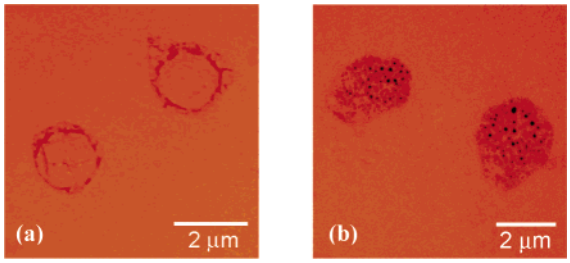

Figure 3. OM images of vesicles cast on silicon wafers from PS_{327}-*b*-$P4VP_{27}$/PFDA complexes with a 1/1 4VP/PFDA molar ratio at a concentration of 0.1 g/L. (a) The initial solution of spherical micelles at 1 g/L has been diluted to 0.1 g/L by addition of pure chloroform, resulting in empty vesicles. (b) The initial solution of spherical micelles at 1 g/L has been diluted to 0.1 g/L by addition of a 4.02×10^{-6} g/L solution of perylene bisimide in $CHCl_3$. The diluted solution has been dialyzed against $CHCl_3$ and then observed. The dark spots inside the vesicles are attributed to clusters of precipitated perylene bisimide molecules. No spots are observed outside the vesicles.

In summary, we have demonstrated that dilution can be used as a stimulus to trigger the reorganization of nonequilibrium spherical micelles into more stable vesicles for PS-*b*-P4VP block copolymer/fluorinated surfactants complexes in $CHCl_3$. Moreover, molecules of interest can be encapsulated inside the vesicles during this process, which opens interesting perspectives for practical applications.

Acknowledgment. Z.H., A.M.J., and J.-F.G. thank the "Fondation Louvain" for financial support (mécénat Solvay).

Supporting Information Available: DLS, AFM, and TEM data on aggregates from various PS-*b*-P4VP/perfluorinated complexes. This material is available free of charge via the Internet at http://pubs.acs.org.

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JA050053M