[12] L. S. Wang, H. S. Cheng, J. Fan, *J. Chem. Phys.* **1995**, *102*, 9480.
[13] L. S. Wang, H. Wu in *Advances in Metal and Semiconductor Clusters. IV. Cluster Materials* (Ed.: M. A. Duncan), JAI, Greenwich, **1998**, pp. 299–343.
[14] We initially optimized the geometries and calculated the frequencies of $SiAl_4$, $GeAl_4$, $SiAl_4^-$, and $GeAl_4^-$ using analytical gradients with polarized split-valence basis sets (6-311 + G*) and a hybrid method known in the literature as B3LYP. Then we refined geometries and calculated frequencies at the second order Møller–Plesset perturbation theory (MP2) level. The energies of the lowest-energy structures were refined using the coupled-cluster (CCSD(T)) method and the more extended 6-311 + G(2df) basis sets. The VDEs and the first ADEs of $SiAl_4^-$, and $GeAl_4^-$ were calculated using the CCSD(T)/6-311 + G(2df) method. All the core electrons were kept frozen in the treatment of the electron correlation at the MP2 and CCSD(T) levels of theory.
[15] Gaussian 98, Revision A.7, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, V. G. Zakrzewski, J. A. Montgomery, Jr., R. E. Stratmann, J. C. Burant, S. Dapprich, J. M. Millam, A. D. Daniels, K. N. Kudin, M. C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G. A. Petersson, P. Y. Ayala, Q. Cui, K. Morokuma, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. Cioslowski, J. V. Ortiz, A. G. Baboul, B. B. Stefanov, G. Lui, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P. M. W. Gill, B. G. Johnson, W. Chen, M. W. Wong, J. L. Andres, M. Head-Gordon, E. S. Replogle, J. A. Pople, Gaussian, Inc., Pittsburgh, PA, **1998**).
[16] The MO pictures were generated by using the MOLDEN3.4 program, G. Schaftenaar, MOLDEN3.4, CAOS/CAMM Center, The Netherlands, **1998**.

Control of Architecture in Block-Copolymer Vesicles**

Hongwei Shen and Adi Eisenberg*

It has been known for some years that highly asymmetric amphiphilic block copolymers can self-assemble in solution to form crew-cut aggregates of an extremely wide range of morphologies.[1] The various morphologies include spheres, rods, bicontinuous structures, lamellae, vesicles, tubes, large compound vesicles (LCVs), hexagonally packed hollow hoops (HHHs), large compound micelles (LCMs), and many others. In such aggregates, the relatively long block forms the core, while the short one forms the corona. A number of other groups have also studied block-copolymer aggregates of various morphologies in recent years.[2, 3] The appeal of this field is, in part, because of the many potential applications of these nano-sized structures with their different morphologies, and in part academic curiosity.

Among the various morphologies, vesicles, including liposomes,[4] are of special interest because of their potential application as encapsulation agents. However the stability of liposomes has been a concern because of the high mobility of the component molecules under ambient conditions; therefore, many attempts have been made to stabilize these liposomes. As polymers have higher stability and lower mobility than small–molecule amphiphilies most of these stabilization strategies consist of the polymerization of the liposomes or the addition of polymeric materials to the liposomes.

Block-copolymer vesicles can be equilibrium structures under some conditions, but can also be kinetically frozen during preparation.[5] The block-copolymer vesicles are robust[3] and are very stable (samples have remained unchanged since 1997) in aqueous solution.[5] Because the studies on block-copolymer vesicles are still in the early stages, only a few attempts at encapsulation have been made.[3, 6]

To utilize block-copolymer vesicles in any given application, the precise control of vesicular parameters, such as vesicle size, wall thickness, number of walls, and space between the walls, is crucial. In our previous studies on the phase diagrams of block-copolymer systems we found that under some conditions the vesicles can be under thermodynamic control.[5] It is believed that the parameters which control the aggregate morphologies, that is the core chain stretching, interfacial tension, and corona repulsion, are also responsible for the control of the vesicular architecture. Thus, variation of these factors allows the properties of the vesicles to be tuned.[1]

A special type of vesicle, the so-called dense "onions", which are found in bulk block-copolymer blends were reported over a decade ago.[7] In block-copolymer solutions, onionlike micelles have been prepared by the stepwise aggregation of two diblocks, first AB and then BC.[8] Onionlike structures have also been reported in small molecule surfactant systems.[9] Recently, it was found that shear can induce the formation of onions from a lamella phase in surfactant systems.[10] By the same strategy, onionlike structures could also be formed in Pluronic systems,[11] and, very recently, onions were prepared from block-copolymer solutions.[12]

Herein we report a new morphology for block copolymers in solution, this consists of concentric vesicles with uniform spacing between the walls; we also describe the preparation in solution of multi-lamella onions in which there is no spacing between the walls, and discuss the control of these morphologies in the context of the other observed vesicular architectures (see Table 1).[1, 5, 13]. Our understanding of this subject is still qualitative, but the evidence obtained suggests that one can exercise control over a variety of vesicular morphologies. Noteworthy is that equally spaced concentric vesicles have been observed in small molecule amphiphiles.[4, 9]

Figure 1 shows concentric vesicles with uniform spaces between the walls, which we refer to as "onions with spaces". From the shadow of the vesicular structures seen by transition electron microscopy (TEM) observation (not shown here),

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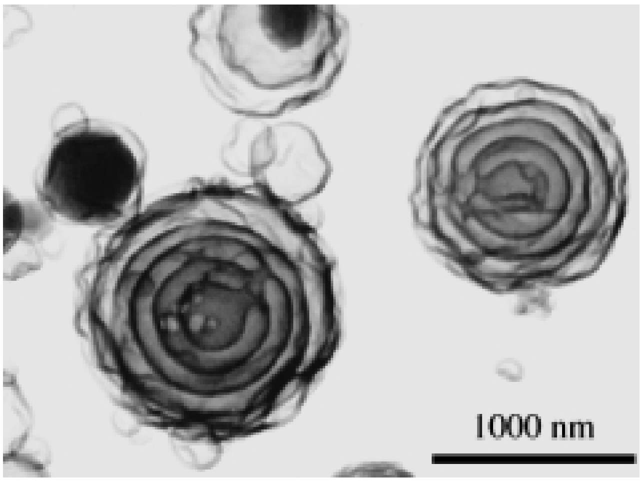

Figure 1. Concentric vesicles with uniform spaces between the walls. These vesicles were prepared from 10 wt% PS_{132}-*b*-PAA_{20} in a dioxane/water mixture with 40 wt% water.

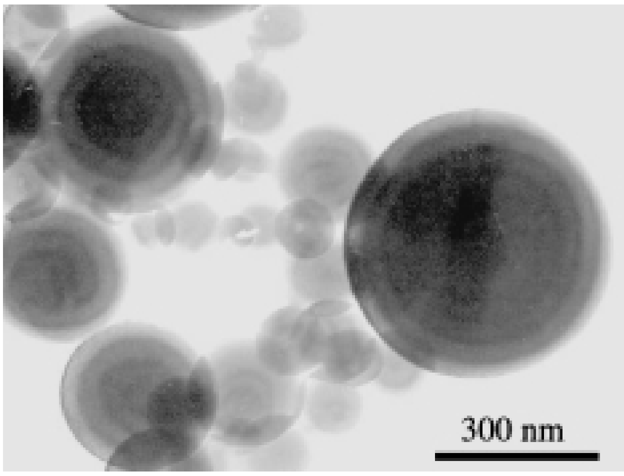

Figure 2. Solid onions prepared from 1 wt% PS_{260}-*b*-$P4VPDecI_{70}$ in THF by dropwise addition of water.

these structures are clearly spherical. The onions with spaces can consist of up to six layers, and their overall diameters can exceed 1 µm (Table 1). The average wall thickness is 22 ± 2 nm and the spacing between the walls is 58 ± 11 nm (95% confidence), based on thirty measurements. The internal layers are fairly smooth, the outer layers are more rugged, probably because this layer is more rapidly dried, compared to those in the interior, during the sample preparation for electron microscopy. Imperfections can be seen between some of the internal wall spaces, for example the connecting regions, which probably helps to maintain the spacing between the walls. The total surface area affected by these imperfections is relatively small.

Figure 2 shows another type of concentric vesicle in which there is no spacing between the walls. These aggregates have a compact multi-lamella vesicular structure and we refer to them as "solid onions". Shadowing indicates that these structures are spherical. The observed onions can be up to 500 nm in diameter and consist of up to eight layers. Because quaternized poly (4-vinyl pyridine) (P4VP), which makes up the corona, has a higher electron density than polystyrene (PS), the corona layer appears as the darker regions, which are 13 ± 1 nm thick. The PS domains appear as gray regions, which are 24 ± 2 nm thick (based on fifty measurements).

The mechanistic aspects of the formation of the solid onions and onions with spaces need to be discussed and compared with those that lead to the formation of other types of vesicles. First, the formation of solid onions is probably similar to the formation of the lamella phase in bulk. Solid onions will be observed when both layers shrink at comparable rates, and the polymer has a composition that would yield the lamella phase in bulk. The small size of the structure also prevents the formation of large flat lamellae, and thus results in the onionlike architecture. Size limitations lead to the formation of curved structures to avoid the thermodynamic penalty of end-cap or rim formation.[1, 7] The polymer PS_{260}-*b*-$P4VPDecI_{70}$ (4VPDecI: 4-vinyl pyridine decyl iodide) has a molecular weight ratio of 50:50, which places it in the lamella region for most bulk systems (another onion-forming polymer, PS_{380}-*b*-$PCEMA_{210}$ (CEMA: 2-cinnamoylethyl methacrylate) has a molecular weight ratio of 45:55[12]). The process is thus similar to that encountered in the earliest preparation of onions in diblock systems.[7] Hence, the process is governed largely by the same thermodynamics that lead to the formation of lamellae in bulk.

In contrast to the above phenomenon, the formation of the onions with spaces is a solution process. The polymer PS_{132}-*b*-PAA_{20} (AA: acrylic acid) is highly asymmetric and would not yield lamellae in bulk. At relatively high polymer concentrations and with the progressive increase of the solvent water content, large vesicles form in solution because of the incompatibility between the core-forming block and the water and in the balance of forces operating in solution self-assembly. As the solvent diffuses out and water diffuses into the large vesicles, progressively smaller vesicles form inside

Table 1. Formation of various vesicular morphologies.

Polymer	M_w/M_n[a]	Conc. [wt%]	Solvent	Type of vesicle	Dimensions [nm] diameter	wall
PS_{410}-*b*-PAA_{20}	1.05	2.0	DMF	uniform unilamella [b]	80–100	≈25
PS_{410}-*b*-PAA_{20}	1.05	3.0	DMF	polydisperse unilamella [b]	100–500	≈25
PS_{200}-*b*-PAA_{18}	1.05	3.0	DMF/THF	entrapped[b]	200–300	≈23
PS_{132}-*b*-PAA_{20}	1.07	10.0	dioxane	onions with spaces	500–1200	22 ± 2
PS_{260}-*b*-$P4VPDecI_{70}$	1.07	1.0	DMF	solid onions[b]	100–500	24 ± 2

[a] Polydispersity (weight average molecular weight over number average molecular weight, M_w/M_n) of the block copolymers as determined by size-exclusion chromatography. [b] Aggregates were prepared by the addition of water to polymer solutions, followed by dialysis.

the large vesicles by the self-assembly of the entrapped polymer under conditions similar to those which led to the formation of the outermost vesicle. The variation in the number of layers depends on the polymer concentration and the size of the outermost vesicles. This formation process may resemble that occurring in small-molecule amphiphile systems.[9] The entrapped vesicles found previously[13] are probably formed by the same solution process.

The onions with spaces and solid onions described above are the latest additions to the family of block-copolymer vesicles (Table 1). The various vesicular structures can be controlled by thermodynamic parameters through such external factors as the diblock composition, the polymer concentration, the type of common solvents, the water content, and the presence of additives. The wall thickness, which affects the strength and the ability of small molecules to penetrate the vesicle walls, is tunable by varying the core-forming block length and the type of common solvent. The shorter the core-forming block, the thinner the wall. The size of the vesicles is mainly controlled by the swelling of the core and by the polymer concentration (Table 1).

Different vesicles are of interest for applications in drug delivery, encapsulation, or in cosmetics. Small vesicles with a narrow size distribution can be targeted at applications that involve size limitations, while the larger vesicles can increase the capacity of encapsulation. Entrapped vesicles may slow down the delivery of some of encapsulated species, but may not be able to function as time-release devices because they lack multiple layers. The presence of chambers between layers allows the onions with spaces to be considered as potential time-release devices which would function by the progressive breaking or erosion of the layers, or by gradual diffusion through the walls. The newly found onions with spaces are unique for block copolymers and extend the range and the control of vesicular structures.

Experimental Section

Block copolymers, PS_{132}-*b*-P(*t*BuA)$_{20}$ (*t*BuA: *tert*-butyl acrylate) and PS_{260}-*b*-$P4VP_{70}$, were synthesized by anionic polymerization.[5] After the hydrolysis of the P(*t*BuA) blocks, the PAA systems were fractionated to remove any homopolystyrene;[5] P4VP blocks were quaternized by using decyl iodide.[14] Onions with spaces were prepared by dissolving 10 wt% PS_{132}-*b*-PAA_{20} in dioxane, then adding water over a three-month period until the water content was 40 wt%, and finally freeze-drying a drop of the colloidal solution on copper grids for TEM observation.[5] Solid onions were prepared by dissolving 1 wt% PS_{260}-*b*-$P4VPDecI_{70}$ in THF, then adding water dropwise at a rate of 1 wt% per minute until the water content was 50 wt%, and finally dialyzing the resulting solution against water. A similar preparation method was also used for preparing other types of vesicles (Table 1) and has been described.[13, 14]

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[1] a) L. Zhang, A. Eisenberg, *Science* **1995**, *268*, 1728; b) L. Zhang, K. Yu, A. Eisenberg, *Science* **1996**, *272*, 1777; c) L. Zhang, C. Bartels, Y. Yu, H. Shen, A. Eisenberg, *Phys. Rev. Lett.* **1997**, *79*, 5034; d) K. Yu, A. Eisenberg, *Macromolecules* **1998**, *31*, 3509; e) K. Yu, C. Bartels, A. Eisenberg, *Macromolecules* **1998**, *31*, 9399; f) N. S. Cameron, M. K. Corbierre, A. Eisenberg, *Can. J. Chem.* **1999**, *77*, 1311.

[2] a) J. P. Spatz, S. Mößmer, M. Möller, *Angew. Chem.* **1996**, *108*, 1673; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1510; b) J. Ding, G. Liu, *Macromolecules* **1997**, *30*, 655; c) G. Liu, *Curr. Opin. Colloid Interface Sci.* **1998**, *3*, 200; d) J. Massey, K. N. Power, I. Manners, M. A. Winnik, *J. Am. Chem. Soc.* **1998**, *120*, 9533; e) A. V. Kabanov, T. K. Bronich, V. A. Kabanov, K. Yu, A. Eisenberg, *J. Am. Chem. Soc.* **1998**, *120*, 9941; f) S. A. Jenekhe, X. L. Chen, *Science* **1998**, *279*, 1903; g) J. J. L. M. Cornelissen, M. Fischer, N. A. J. M. Sommerdijk, R. J. M. Nolte, *Science* **1998**, *280*, 1427; h) E. Kramer, S. Forster, C. Goltner, M. Antonietti, *Langmuir* **1998**, *14*, 2027; i) R. R. Netz, J. F. Joanny, *Macromolecules* **1998**, *31*, 5123; j) F. Caruso, R. A. Caruso, H. Möhwald, *Science* **1998**, *282*, 1111; k) R. R. Netz, *Europhys. Lett.* **1999**, *47*, 391; l) A. Harada, K. Kataoka, *Science* **1999**, *283*, 65; m) Z. Li, Y. Liang, F. Li, *Chem. Commun.* **1999**, *16*, 1557; n) K. Fischer, M. Gerle, M. Schmidt, *Polym. Mater. Sci. Eng.* **1999**, *80*, 133.

[3] a) B. M. Discher, Y. Y. Won, D. S. Ege, J. C. M. Lee, F. S. Bates, D. E. Discher, D. A. Hammer, *Science* **1999**, *284*, 1143; b) B. M. Discher, Y. Y. Won, J. C. M. Lee, H. Bermudez, F. S. Bates, D. A. Hammer, D. E. Discher, *Biophys. J.* **2000**, *78(1)*, 1950.

[4] *Vesicles* (Ed.: M. Rosoff), Dekker, New York, **1996**, Chap. 9–10.

[5] a) H. Shen, A. Eisenberg, *J. Phys. Chem. B* **1999**, *103*, 9473; b) H. Shen, A. Eisenberg, *Macromolecules* **2000**, *33*, 2561.

[6] J. Ding, G. Liu, *J. Phys. Chem. B* **1998**, *1023*, 6107.

[7] a) D. J. Kinning, K. I. Winey, E. L. Thomas, *Macromolecules* **1988**, *21*, 3502; b) E. L. Thomas, J. R. Reffner, J. Bellare, *Colloq. Phys.* **1990**, *C7* (363), 15.

[8] a) K. Prochazka, T. J. Martin, S. E. Webber, P. Munk, *Macromolecules* **1996**, *29*, 6526; b) M. R. Talingting, P. Munk, S. E. Webber, Z. Tuzar, *Macromolecules* **1999**, *32*, 1593.

[9] a) A. Sein, J. B. F. N. Engberts, *Langmuir* **1993**, *9*, 1714; b) D. Danino, Y. Talmon, R. Zana, *J Colloid Interface Sci.* **1997**, *185*, 84; c) M. Bergmeier, M. Gradzielski, H. Hoffmann, K. Mortensen, *J. Phys. Chem. B* **1999**, *103*, 1605.

[10] a) F. Gauffre, D. Roux, *Langmuir* **1999**, *15*, 3738; b) O. Regev, F. Guillemet, *Langmuir* **1999**, *15*, 4357.

[11] J. Zipfel, P. Lindner, M. Tsianou, P. Alexandridis, W. Richtering, *Langmuir* **1999**, *15*, 2599.

[12] J. Ding, G. Liu, *Macromolecules* **1999**, *32*, 8413.

[13] Y. Yu, A. Eisenberg, *J. Am. Chem. Soc.* **1997**, *119*, 8383.

[14] H. Shen, L. Zhang, A. Eisenberg, *J. Am. Chem. Soc.* **1999**, *121*, 2728.

Hydrogen-Bonded Hexamolybdenum Clusters: Formation of Inorganic – Organic Networks[**]

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The increasing importance of solid materials in catalysis, nonlinear optics, chemical sensors, separation technology, and electronics has created a demand to control the chemical and physical properties of solids.[1] Solution chemists typically approach this problem by synthesizing discrete molecules that spontaneously self-assemble into extended arrays.[2] The significance and impact of self-assembly are demonstrated by the porous zeolites that combine the acidic properties of the aluminosilicate with the channels and pores of the

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