

Hollow Spheres Self-Assembled by a Tetraphenylethylene Macrocycle and Their Transformation to Bird Nests under Ultrasound

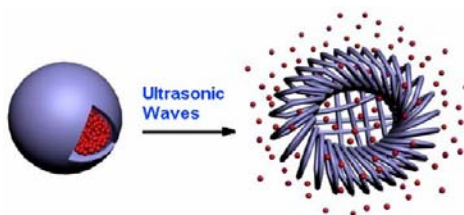
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ABSTRACT



A new tetraphenylethylene macrocycle easily self-assembled into both intrinsic pores and extrinsic pores in crystal and hollow spheres in precipitates. The hollow spheres could be transformed into bird nests composed of nanorods under ultrasound, which could be used to load and controllably release anticancer drugs.

Porous materials are attracting increasing interest because of their importance in separation, storage, and catalysis. Among the methods for preparation of the porous materials, using organic macrocycles to self-assemble the porous materials has special advantages because they can

form both intrinsic porosity and extrinsic porosities.^{1–21} The inherent cavity of the macrocycle could easily pile into a porous channel to give intrinsic porosity which could be modified in diameter, shape, and polarity by the change of inherent cavity.^{1–10} In contrast, the extrinsic porosity^{12–21} from the arrangement of the macrocycles can exist as

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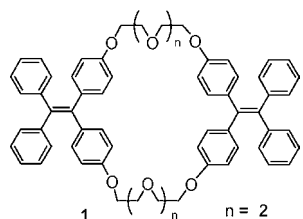


Figure 1. Structure of macrocyclic molecule **1**.

discrete unfilled space, with a hope to form larger size of pores and encapsulated big guest molecules. However, to date, no significant amount of research has been done in this area.

Tetraphenylethylene (TPE) and its derivatives have a well-known aggregation-induced emission (AIE) effect, displaying extensive application potential in optoelectronic materials and bio/chemosensors.^{22,23} Due to repulsive forces, the four phenyl groups of the TPE molecule are not completely conjugated with the double bond and make TPE a twisted molecule. Therefore, no π - π stacking interactions but multiple CH- π hydrogen bonds between TPE molecules or its derivatives exist in crystal structure,^{24,25} which is the main reason why they have an AIE effect. The absence of π - π stacking interactions also suggests that packing of TPE molecules in the aggregate state is not very close, which gives them the possibility to form extrinsic void space in solid state.¹¹ It is true that polymer scaffolds and metal-organic frameworks based on TPE are microporous.^{26,27} Furthermore, due to sensitivity to the environment, the AIE effect of macrocycles based on TPE can probably be used as self-signals for monitoring the process of self-assembly. But macrocyclic compounds composed of TPE for self-assembling porous materials have not yet been reported. Here, we report that a TPE macrocycle could easily self-assemble into hollow micro-/nanospheres as well as intrinsic and extrinsic porous channels.

Macrocycle **1** (Figure 1) was synthesized by connecting two TPE molecules with two triethylene glycol chains in

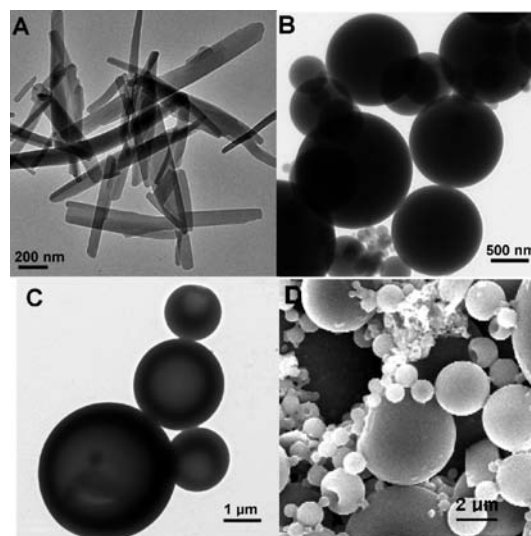


Figure 2. Electron microscopy images of a suspension of **1** in water and THF with different water percentages: (A) TEM image in 70% water; (B) TEM image in 90% water; (C) TEM images in 95% water; (D) FE-SEM image in 95% water. [**1**] = 2.5×10^{-3} M.

good yield. Solution of **1** in THF did not emit, but the solid had strong fluorescence. When water was added into the THF solution and a turbid solution appeared, the resultant suspension emitted strong fluorescence, indicating that macrocycle **1** was an AIE compound. Meanwhile, when the content of water increased from 65% to 95% (volume percentage, as below), the emission λ_{\max} increased from 448 to 473 nm (Figure S11, Supporting Information). The fluorescence quantum yield of the suspension of **1** in 70, 90, and 95% water was 9.1, 10, and 15%, respectively, using quinine sulfate as a reference standard.

Interestingly, not only the fluorescence spectrum but also the morphology of aggregates of **1** in the mixed solvent changed with water fraction. It was disclosed by TEM images that the aggregates were nanorods in a suspension with 70% water (Figure 2A). When the water was increased to 90%, the aggregates became solid spheres (Figure 2B). Surprisingly, hollow spheres were obtained after the water content was elevated to 95% or more. TEM images revealed that the diameter of the hollow spheres was distributed from about 1 to 8 μm , and the shell width of the hollow spheres was in the range of 500 nm to 1 μm (Figure 2C and Figures S12–S13, Supporting Information). The FE-SEM image disclosed that the suspension of **1** in 95% water was composed of spherical aggregates, and the surface of many of these was sunken and some of them were broken, showing that the spheres were truly hollow (Figure 2D and Figures S14–S15, Supporting Information). The formation of the giant hollow spheres was very reliable and could be easily repeated as long as water was quickly added to the solution of **1** in THF until at a percentage of 95% or more. Due to the challenges of obtaining cell-sized

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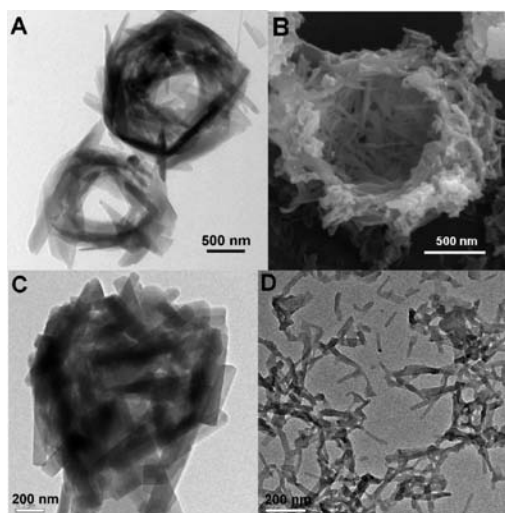


Figure 3. (A) TEM image and (B) FE-SEM image of a suspension of **1** in 95% water with ultrasonic treatment for 1.5 h. (C) TEM image with ultrasonic treatment for 45 min. (D) TEM image with ultrasonic treatment for 4 h. $[1] = 2.5 \times 10^{-3}$ M.

vesicles, these kinds of giant hollow sphere have a potential to be used as artificial cells.^{28,29}

After standing at room temperature for 3 days, the nanorods in 70% water grew bigger and emitted more intensive fluorescence, while the solid spheres in 90% water converted into nanorods and the emission λ_{max} decreased from 470 to 450 nm. However, the hollow spheres in 95% water were very stable and no change in morphology or fluorescence was observed after they were allowed to stand for more than two weeks.

However, when treated with ultrasonic waves, the hollow sphere reassembled into nanorods which could form an aggregate just like a bird nest (Figure 3A,B and Figures S16 and S17, Supporting Information). As ultrasonic time was increased from 45 min to 1.5 and 4 h, the width of the nanorods decreased from about 100 to 70 nm and 30 nm, respectively, while their length was stable at about 600 nm. Meanwhile, after 45 min of ultrasonic treatment, the produced nanorods were on the shell of the sphere and the round aggregate arranged by the nanorods was still enclosed (Figure 3C). After 1.5 h, the hollow sphere opened in one direction, but most of the nanorods remained at their original position on the shell, which led to a bird nest like aggregate (Figure 3A,B). After 4 h, the nanorods were totally dispersed and no longer arranged around a cycle while their width was obviously reduced (Figure 3D). In addition, the emission λ_{max} of the fluorescence spectrum of the hollow spheres decreased with ultrasonic time (Figure S18, Supporting Information). After 1.5 and 4 h of ultrasonic treatment, the wavelength

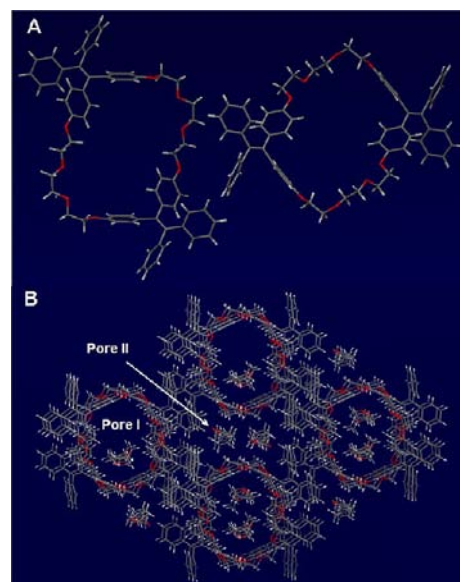


Figure 4. (A) Structures of **1** in single crystal from water and THF; (B) intrinsic and extrinsic channels packed by **1**.

was decreased to 450 and 437 nm from 473 nm, respectively. Notably, the hollow spheres were not altered under ultrasonic waves if they were suspended in pure water without THF. Therefore, the transformation of the aggregates from hollow spheres to nanorods was not a simple breakage of the spheres, but a change resulting from a dissolving and reassembling process. In 90% water in which solid spheres were formed, the solid spheres could be transformed into nanorods not only by ultrasound but also by standing at room temperature, corroborating the dissolving and reassembling process.

X-ray diffraction of a single crystal of **1** obtained from water and THF³⁰ disclosed that **1** had an inherent rectangular cavity with 1.5 nm length and 0.7 nm width (Figure 4A). The rectangular cavities of **1** could pack into intrinsic cubic channels, which were filled with THF molecules (THF/**1** 2:1) (Figure 4B, pore I). Because of the twisted conjugated structure of **1**, two neighboring macrocyclic molecules were staggered along the channel direction (axis a) rather than eclipsed. Between four intrinsic cubic channels, one extrinsic cubic channel with 1.2 nm length and 0.7 nm width was formed, which was also filled with THF molecules (THF/**1** 2:1) (Figure 4B, pore II). It could also be regarded that the extrinsic cubic channel was formed through the piling up of rectangles composed of four molecules of **1**. Therefore, the interior of one molecule of **1** made up one part of the intrinsic channel and simultaneously the exterior of it became one part of extrinsic channel. This packing gave a very large exposed molecular

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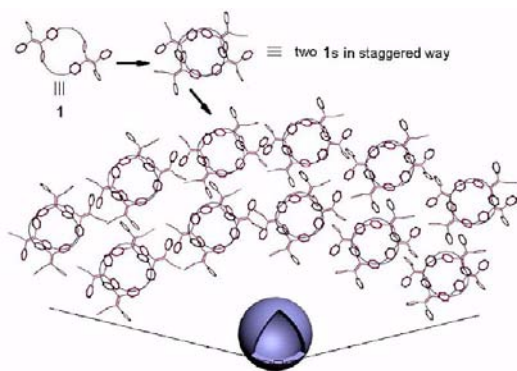


Figure 5. Schematic illustration for the formation of a hollow sphere.

surface in the solvated channels of **1** and one molecule of **1** could combine four molecules of THF.

As expected, no π – π stacking interactions were found between macrocycles, but there were many ArH– π , CH– π , and ArH–O hydrogen bonds between aromatic rings. In addition, between the phenyl rings and solvent THF, there were ArH–H (2.288 Å), ArH–O (2.556 Å), and ArH–C (2.823 Å) interactions. These interactions played a key role in the formation of both intrinsic and extrinsic porosity.

The reason why porous aggregates of **1** were formed in a smaller amount of water was probably related to the precipitating velocity. When a smaller amount of water was added into the solution of **1** in THF, the molecules of **1** precipitated slowly and could efficiently pack each other so that no large cavity could be seen by TEM. When water was increased to 95%, the macrocyclic molecules precipitated too fast to pack efficiently, therefore, hollow spheres were obtained. It was not difficult to deduce from the crystal structure of **1** that hollow spheres could be produced if pore II was composed of more than four macrocyclic molecules. These molecules were staggered and, due to hydrophobic force, could arrange around a cycle to form a round cavity as shown in Figure 5.

According to structure theory, a small repulsive force between phenyl groups and a large conjugation of them with the double bond will make **1** more stable. However, more conjugation will lead to a smaller dihedral angle between the phenyl plane and double bond plane, which would lead to a larger repulsive force. As a result, a balance between the repulsive force and conjugation effect or between the dihedral angles of 0–90° for molecule of **1** arrived.²⁵ Because of crowded phenyl groups, a bigger dihedral angle instead of more conjugation will stabilize the molecule. Therefore, the average dihedral angle of the four phenyl rings in the crystal structure of **1** from a mixed solvent of water and THF was 51.71°, which was larger

than the middle value (45°) between 0° and 90°. Compared with the nanorod, the spherical aggregate could emit fluorescence with a longer wavelength (up to a difference of 36 nm) and also had a larger absorption λ_{max} (a difference of about 15 nm) in UV–vis spectrum (Figure S19, Supporting Information), indicating that the molecule of **1** in spheres had more conjugation, which in turn led to less dihedral angle and bigger repulsive force. A single crystal structure³⁰ of **1** from dichloromethane and methanol emitted blue fluorescence with a wavelength 10 nm shorter than that of the single crystal from THF and water (Figure S20, Supporting Information), but had an average dihedral angle of 54.71° which was 2.8° larger than that of the later crystal (Figures S21–S22, Supporting Information). Furthermore, the average twisted angle³¹ (7.97°) of the double bond in the former crystal was also less than that (11.72°) in the crystal from water and THF. This result confirmed that the molecule of **1** that emitted shorter wavelength of light had a less repulsive force. Therefore, spherical aggregates that emitted a longer wavelength of light were composed of higher energy of **1** and could spontaneously transform into nanorods by standing and ultrasonic treatment. As the water content was increased, the large hydrophobic force could make the molecule of **1** exist in a conformation with higher energy. Powder X-ray diffraction revealed that nanorods and solid spheres displayed many strong and sharp peaks, but the hollow spheres almost exhibited only a weak and broad peak at low angles (Figures S23–S25, Supporting Information), demonstrating that the precipitating was so fast that **1** could not form ordered pack in hollow spheres.²⁴ Treated by ultrasonic waves, the powder X-ray diffraction pattern gave many strong sharp peaks, indicating that the amorphous hollow spheres were transformed into more stable crystalline nanorods.

The potential for the loading and releasing of guest molecules by the hollow spheres was demonstrated using a picric acid salt of the anticancer drug procarbazine (here abbreviated as picrate) as a representative example. By UV–vis measurement of the picrate, the loading amount of the picrate was calculated to be 5.3 mg per 100 mg of **1**. The release of the picrate was fast under ultrasonic waves. In 1.5 and 3 h, 57% and 92% of the loaded picrate was released, respectively (Figure S26, Supporting Information). If left to stand at room temperature, only 9.8% and 62% of the picrate were released in 12 and 72 h, respectively (Figure S27, Supporting Information).

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Supporting Information Available. Experimental details, XRD patterns, more crystal structures, and images. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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The authors declare no competing financial interest.