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# Self-Assembled Interwoven Cages from Triptycene-Derived Bis-Macrotricyclic Polyether and Multiple Branched Paraquat-Derived Subunits

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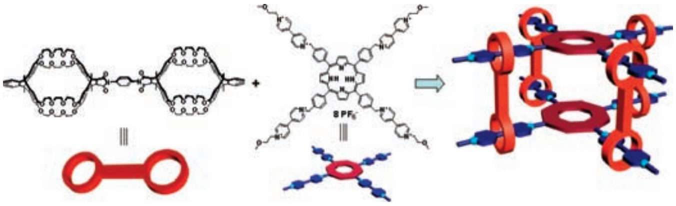
## ABSTRACT



**On the basis of formation of a 1:2 complex between the triptycene-derived bis-macrotricyclic polyether and the paraquat derivative, two novel well-defined interwoven supramolecular cages were constructed by the [3 + 2] and [4 + 2] self-assembly of the polyether and trifurcated and cross paraquat-derived subunits under millimolar concentrations, respectively.**

Self-assembled molecular containers, such as supramolecular cages, have attracted great interest for not only their aesthetic structures but also their potential applications in many research areas.[1] Over the past two decades, many types of self-assembled molecular cages have been constructed, which can be divided into two categories according to the building subunits: metal−organic assembled cages and organic assembled cages. Relying on coordinative bonds which offer greater strength and more rigidity, a variety of metal−organic assembled cages with different shapes[2] and amazing prospects[3] have been artfully synthesized. The organic assembled cages could be achieved by a variety of forces, including hydrogen bonds, hydrophobic effects, and $\pi-\pi$ interactions, which offer greater plasticity and faster equilibration.[4] These weak multi-interactions in organic assembled cages provide many potential opportunities to encapsulate neutral and/or charged guests whose size, shape, and chemical exteriors complement those of the cage's inner surface. Based on the facile synthesis and recognition properties of macrocyclic hosts, several types of organic assembled cages[5] have now been synthesized, and they exhibited broad prospects in catalysis,[6] photochemistry,[7] miscellaneous reactions,[8] physical organic chemistry,[9] and trapping or stabilizing reactive

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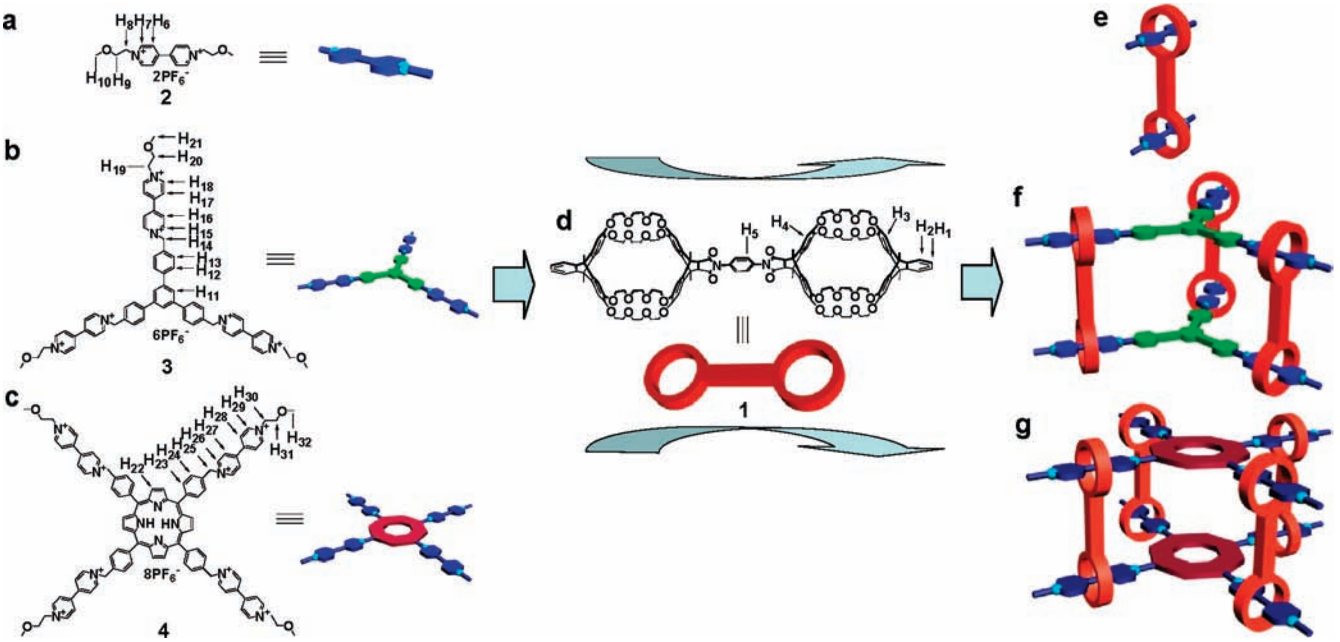

**Figure 1.** Graphical representations and proton designations of (a) paraquat derivative **2**, (b) trifurcated paraquat-derived subunit **3**, (c) cross-shaped paraquat-derived subunit **4**, (d) bis-macrotricyclic polyether **1**, (e) [3]pseudorotaxane $\mathbf{1{\bullet}2_2}$, (f) [3 + 2] self-assembled cage $\mathbf{1_3{\bullet}3_2}$, and (g) [4 + 2] self-assembled cage $\mathbf{1_4{\bullet}4_2}$.

intermediates.[10] However, the construction of well-defined self-assembled cages, especially the multicomponent organic self-assembled cages, still remains a considerable challenge mainly due to the limit of the hosts or the building blocks with multirecognition sites.

Recently, we[11] reported a novel triptycene-derived cylindrical macrotricyclic polyether containing one central cavity and two lateral crown ether cavities, which showed interesting guest-dependent complexation with different functional paraquat derivatives and secondary ammonium salts. More recently, we also synthesized a new triptycene-derived bis-macrotricyclic host **1** with multicavities and multirecognition sites (Figure 1d) and found that it could self-assemble with 2 equiv of bis-secondary ammonium salts to form an acid–base switchable molecular handcuff.[12] Furthermore, we deduced that the bis-macrotricyclic host could also form a 1:2 complex $\mathbf{1{\cdot}2_2}$ (Figure 1e) with 2 equiv of the paraquat derivative **2**. Then, on the basis of formation of $\mathbf{1{\cdot}2_2}$, we could construct two novel multicomponent interwoven supramolecular cages $\mathbf{1_3{\cdot}3_2}$ (Figure 1f) and $\mathbf{1_4{\cdot}4_2}$ (Figure 1g) by the [3 + 2] and [4 + 2] self-assembly of the host **1** and trifurcated and cross-shaped paraquat-derived subunits **3** and **4**, respectively. Herein, we report the recent results in this respect.

According to the similar method we described before, we conveniently synthesized the trifurcated paraquat derivative **3** in 37.6% yield by the reaction of 1-(2-methoxyethyl)-4,4′-bipyridine hexafluorophosphate **5**[11e] with 1,3,5-tris(*p*-bromomethylphenyl)benzene[13] in DMF. Similarly, we obtained the cross-shaped subunit **4** in 44.7% yield by the reaction of **5** with 5,10,15,20-tetrakis-(α-bromo-*p*-tolyl)porphyrin **7**[14] (Scheme 1).

We first tested the complexation between host **1** and paraquat derivative **2** in solution. In the $^1$H NMR spectrum of a 1:2 mixture of **1** and **2** (4 mM), recorded in $CDCl_3$/$CD_3CN$ (1:1, v/v), one set of signals were only observed,

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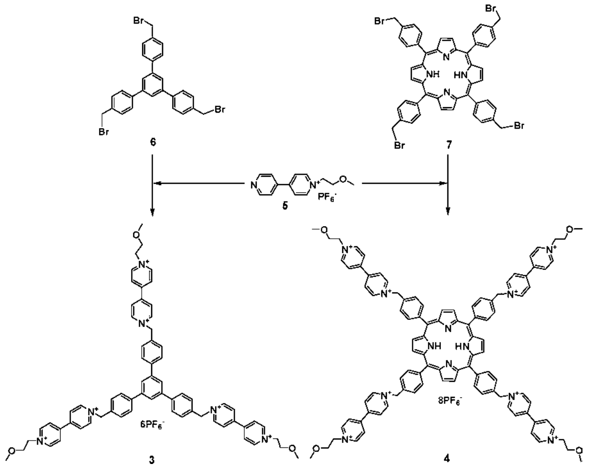
**Scheme 1.** Synthesis of the Paraquat Derivatives **3** and **4**



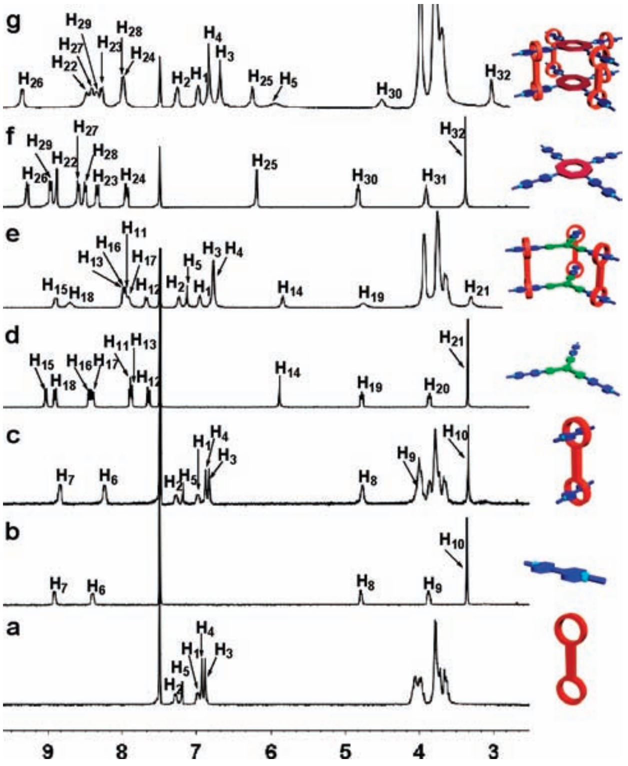


**Figure 2.** Partial $^1H$ NMR spectra (300 MHz, $CD_3CN/CDCl_3$ = 1:1, 298 K) of (a) free **1**, (b) free **2**, (c) **1** and **2** (molar ratio 1:2), (d) free **3**, (e) **1** and **3** (molar ratio 3:2), (f) free **4**, and (g) **1** and **4** (molar ratio 2:1). $[\mathbf{1}]_0$ = 3.0 mM.

which indicated that the fast-exchange complexation between **1** and **2** occurred. The resonances of the complex were assigned by its 2D NMR experiments.[15] As shown in Figure 2c, the protons $H_6$ ($\Delta\delta = -0.15$ ppm) and $H_7$ ($\Delta\delta = -0.07$ ppm) of the pyridinium ring and the protons $H_3$ ($\Delta\delta = -0.05$ ppm) and $H_4$ ($\Delta\delta = -0.05$ ppm) of **1** all showed upfield shifts. Meanwhile, no intermolecular cross-peaks between proton $H_8$ adjacent to the bipyridinium ring in **2** and crown ether protons in **1** were observed in the $^1H-^1H$ ROESY 2D NMR spectrum of the complex. These results indicated that two guests of **2** could thread the two central cavities of **1**, respectively, to form the 1:2 complex $\mathbf{1}\cdot\mathbf{2}_2$.[11] Furthermore, $^1H$ NMR spectroscopic titrations afforded a quantitative estimate between **1** and **2** by monitoring the changes of the chemical shift of proton $H_6$. The results showed that a 1:2 complex $\mathbf{1}\cdot\mathbf{2}_2$ was formed by a mole ratio plot. The two cavity bonding sites behave independently, and the average association constant ($K_{av}$) was calculated to be 9.0 (±0.4) × $10^3$ $M^{-1}$ by the Scatchard plot.[16] The electrospray ionization mass spectrum (ESI MS) provides more evidence for the formation of complex $\mathbf{1}\cdot\mathbf{2}_2$. Consequently, the strong peaks at *m/z* 740.0 for $[\mathbf{1}\cdot\mathbf{2}_2\text{-}4PF_6]^{4+}$, 1034.9 for $[\mathbf{1}\cdot\mathbf{2}_2\text{-}3PF_6]^{3+}$, and 1343.0 for $[\mathbf{1}\cdot\mathbf{2}\text{-}2PF_6]^{2+}$ were observed.[15]

Formation of complex $\mathbf{1}\cdot\mathbf{2}_2$ encouraged us to further design and construct self-assembled molecular cages. The first evidence for the formation of the molecular cages in solution came from the $^1H$ NMR spectrometry. As shown in Figure 2, when a solution of **3** (2 mM) in $CDCl_3$ and $CD_3CN$ (1:1, v/v) was mixed with 1.5 equiv of **1**, only one set of well-defined peaks was found (Figure 2e), which indicated a new complex between **1** and **3** formed and the complexation was also a fast-exchange process. The protons $H_{16}$ ($\Delta\delta = -0.49$) and $H_{17}$ ($\Delta\delta = -0.48$) of the paraquat rings and protons $H_3$ ($\Delta\delta = -0.11$) and $H_4$ ($\Delta\delta = -0.14$) of **1** showed significant upfield shifts due to the stronger shielding effect of the aromatic rings, while no obvious signal changes of the protons in the substituent groups of paraquat rings were observed. Moreover, no intermolecular cross-peaks between proton $H_{19}$ or $H_{14}$ in **3** and the protons of crown ether in **1** were also observed in the $^1H-^1H$ ROESY 2D NMR spectrum. These observations suggested the paraquat subunits in **3** took the same complexation mode as that of the complex $\mathbf{1}\cdot\mathbf{2}_2$, which resulted in a new cage-like assembly $\mathbf{1}_3\cdot\mathbf{3}_2$ (Figure 1f). Formation of the prism-shaped supramolecular cage $\mathbf{1}_3\cdot\mathbf{3}_2$ was also evidenced by its ESI MS spectrum, in which a peak at *m/z* 1420.9 for $[\mathbf{1}_3\cdot\mathbf{3}_2\text{-}7PF_6^-]^{7+}$ was observed.[15]

Similar to the complex $\mathbf{1}_3\cdot\mathbf{3}_2$, the $^1H$ NMR spectrum of a 2:1 mixture of **1** and **4** (2 mM) in $CDCl_3/CD_3CN$ (1:1, v/v) solution also displayed one set of characteristic resonances (Figure 2g), which were significantly different from those of host **1** (Figure 2a) and guest **4** (Figure 2f). The resonances of the complex were assigned by its $^1H-^1H$ COSY spectrum and the $^1H$ NMR titrations.[15] It was noted that the protons $H_{27}$, $H_{28}$, $H_{29}$ of the paraquat rings and the aromatic protons $H_3$ and $H_4$ of the host all showed upfield shifts. Meanwhile, the proton signals of $H_{25}$ and $H_{26}$ shifted downfield slightly, and those of $H_{30}$ and $H_{32}$ of the paraquat rings shifted upfield significantly, which might be attributed to a slight movement

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(15) See Supporting Information for the details.

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of host **1** along the paraquat axles away from the center of guest **4**. Especially, it was found that the signal of proton $H_5$ in **1** shifted dramatically to upfield ($\Delta\delta = -1.26$ ppm) and broadened, which might be due to the strong shielding effect of the porphyrin ring of **4**. These observations suggested that the proton $H_5$ might be in the vertical direction of the porphyrin plane, and the target self-assembled interwoven cage $\mathbf{1}_4\bullet\mathbf{4}_2$ (Figure 1g) thus formed. Formation of the molecular cage $\mathbf{1}_4\bullet\mathbf{4}_2$ was also unambiguously evidenced by its ESI MS spectrum (Figure 3).

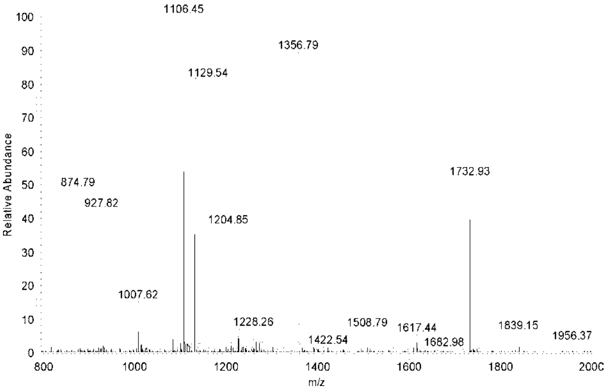

**Figure 3.** ESI MS spectrum of complex $\mathbf{1}_4\bullet\mathbf{4}_2$. Peaks at *m/z* 1732.9 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}8PF_6^-]^{8+}$, 1508.8 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}9PF_6^-]^{9+}$, 1356.8 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}10PF_6^-]^{10+}$, 1204.9 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}12PF_6^- + H^+]^{11+}$, 1129.5 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}12PF_6^- + Na]^{12+}$, 1106.5 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}12PF_6^-]^{12+}$, 1007.6 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}13PF_6^-]^{13+}$, 927.8 for $[\mathbf{1}_4\bullet\mathbf{4}_2\text{-}14PF_6^-]^{14+}$, and 874.8 for $[\mathbf{1}_4\bullet\mathbf{4}_2 - 15PF_6^- + H_2O]^{15+}$.

As reported before,[17] DOSY NMR techniques are useful and reliable methods for the analysis of shape changes in supramolecular systems, thus potentially confirming the construction of supramolecular architectures. Therefore, to further determine the formation of the self-assembled interwoven cages $\mathbf{1}_3\bullet\mathbf{3}_2$ and $\mathbf{1}_4\bullet\mathbf{4}_2$, a series of diffusion-ordered NMR experiments in $CDCl_3/CD_3CN$ (1:1, v/v) were carried out. First, the hydrodynamic radius (or Stokes radius) of $\mathbf{1}\cdot\mathbf{2}_2$, **3**, and **4** were determined to be 21.26, 21.61, and 24.24 Å, respectively.[15] Under the same conditions, it was found that a 2:1 mixture of **1** and **4** (2 mM) showed only one species with a hydrodynamic radius of 34.80 Å. By simplifying the supramolecular cage $\mathbf{1}_4\bullet\mathbf{4}_2$ to a geometric cube, we then calculated the circumcircle radius of the geometric cube to be 32.70 Å, which was well consistent with the result determined by a diffusion-ordered NMR experiment. Similarly, a 3:2 ratio of **1** and **3** (2 mM) in $CDCl_3/CD_3CN$ (1:1, v/v) gave only one species with a hydrodynamic radius of 32.70 Å, which was also consistent with the result calculated by simplifying the self-assembled cage $\mathbf{1}_3\bullet\mathbf{3}_2$ to a prism-shaped geometry.[15] These results led us to conclude that the self-assembled interwoven cages $\mathbf{1}_3\bullet\mathbf{3}_2$ and $\mathbf{1}_4\bullet\mathbf{4}_2$ were formed at the tested conditions.

Similar to the multicomponent assemblies reported before,[18] we believed that the [3 + 2] and [4 + 2] self-assemblied processes between host **1** and the guests **3** and **4** were also favored for thermodynamic reasons. First, the bonding sites of the constituents in the self-assembled interwoven cages $\mathbf{1}_3\bullet\mathbf{3}_2$ and $\mathbf{1}_4\bullet\mathbf{4}_2$ were all occupied, and the assemblies thus attained the thermodynamically most stable state, which was in accordance with the energy-related principle of maximal site occupancy.[19] Second, entropic factors also favor the formation of the largest number of product species in one system. Thus, compared to the formation of the polymeric supramolecular array which would have displayed a considerable entropy loss, the small and discrete supramolecular cages are also apt to form. These provide the theoretical support for formation of the self-assembled cages $\mathbf{1}_3\bullet\mathbf{3}_2$ and $\mathbf{1}_4\bullet\mathbf{4}_2$.

In conclusion, we have shown that the triptycene-derived bis-macrotricyclic host **1** could form a 1:2 stable complex with paraquat derivative **2**. On the basis of the formation of complex $\mathbf{1}\cdot\mathbf{2}_2$, we have successfully constructed two novel multicomponent interwoven organic supramolecular cages by the [3 + 2] and [4 + 2] self-assembly of host **1** and trifurcated and cross paraquat-derived subunits **3** and **4**, respectively. We believe that the results presented here will offer opportunities for further construction of novel self-assembled organic containers and molecular machines, which will thus find potential applications in supramolecular chemistry.

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**Supporting Information Available:** Experimental procedures and characterization data for new compounds. $^1H-^1H$ COSY, $^1H-^1H$ ROESY, $^1H$ NMR titration, DOSY experiments, and ESI-MS spectra of complexes $\mathbf{1}\cdot\mathbf{2}_2$ and $\mathbf{1}_3\bullet\mathbf{3}_2$. Determination of the average association constants ($K_{av}$) for $\mathbf{1}\cdot\mathbf{2}_2$. This material is available free of charge via the Internet at http://pubs.acs.org.

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