Dynamic Chemistry

DOI: 10.1002/ange.201004304

Template-Directed Syntheses of Rigid Oligorotaxanes under Thermodynamic Control**

*Matthew E. Belowich, Cory Valente, and J. Fraser Stoddart**

The application of mechanically interlocked molecules (MIMs) as molecular switches for nanoelectronics,[1] as molecular actuators for constructing artificial muscles,[2] and in controlling the release of molecules stored in mesoporous silica nanoparticles[3] remains an area of intense activity in research. Dynamic covalent chemistry[4] (DCC), a process whereby covalent bonds are formed reversibly under thermodynamic control, hence possessing an element of "proof-reading" or "error-checking", has emerged as a valuable tool in the construction of MIMs, such as rotaxanes,[5] catenanes,[6] suitanes,[7] trefoil knots,[8] Borromean rings,[9] and Solomon knots.[10] The main attribute of DCC is that it operates under equilibrium such that the formation of undesired, kinetically competitive intermediates will eventually make their way back to the thermodynamically most stable product.

Oligorotaxanes are commonly prepared employing a "threading-followed-by-stoppering" approach[11] (Figure 1, Strategy A), wherein preformed rings locate around well-chosen recognition units in a thread that is stoppered subsequently. This approach suffers from the fact that it does not provide complete control over the number of threaded rings—which often do not encircle every recognition unit—and, moreover, stoppering conditions must be mild and chosen carefully. Alternatively, the "clipping" approach[12] (Figure 1, Strategy B) takes advantage of noncovalent bonding interactions to control ring formation by templation, starting from acyclic precursors and using every single recognition site. With adequate system design, equilibrating reactions including olefin metathesis,[13] disulfide[5c,14] and imine bond formation[5b,15] have all been utilized extensively in the syntheses of MIMs. For example, it has been demonstrated[12f] that this "clipping" approach is effective in the near quantitative synthesis of oligorotaxanes in a one-pot, multicomponent self-assembly process from 1) a dumbbell component containing *n* -$CH_2NH_2^+CH_2$- recognition sites and 2) *n* equivalents each of 2,6-pyridinedicarboxaldehyde (**5**) and tetraethyleneglycol bis(2-aminophenyl)ether (**6**). The [2]rotaxane **1R**·PF_6 composed of bis(3,5-dimethoxybenzyl)-ammonium hexafluorophosphate and the [24]crown-8 derivative (red ring in Figure 2) is the quantitative outcome of (1) plus (2) in CD_3CN within 5 min of mixing the starting materials. In this self-assembly process, involving -$CH_2NH_2^+CH_2$- activation/recognition sites, the clipping reaction is driven by a combination of DCC and noncovalent bonding interactions[15b] including [N^+–H···X] hydrogen bonds and [N^+–C–H···X] (X = O or N) interactions, as well as [π···π] stacking interactions between the dumbbell and the encircling rings.

Whereas much research has been devoted to the syntheses and applications of such MIMs, very little research has been dedicated to controlling their overall *conformations*. From computational investigations,[16] the above-mentioned oligorotaxanes were predicted to assume flexible conformations. We suspected that [π···π] interactions between adjacent encircling rings would not only provide added stability to the oligorotaxanes, but would also lend linearity and rigidity

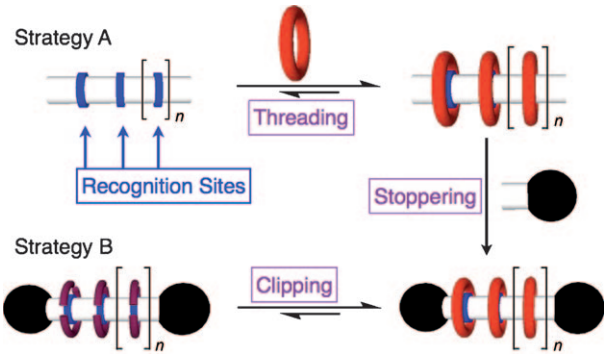

Figure 1. Two different strategies employed in the template-directed synthesis of oligorotaxanes. Strategy A: the kinetically controlled (usually) "threading-followed-by-stoppering" approach. Strategy B: the thermodynamically controlled "clipping" approach. Strategy B: the thermodynamically controlled "clipping" approach. Strong hydrogen-bond-donor recognition sites are indicated in blue, while the complementary acceptor sites are associated with red rings.

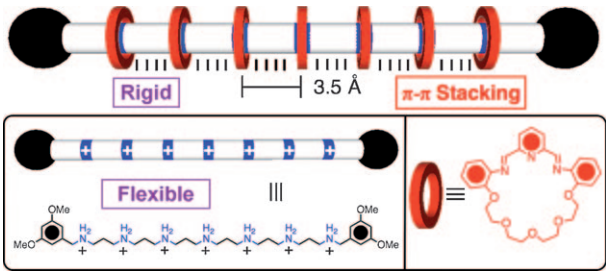

Figure 2. Design of rigid rodlike oligorotaxanes based on [π···π] stacking interactions between aromatic rings separated by 3.5 Å.

[*] M. E. Belowich, Dr. C. Valente, Prof. J. F. Stoddart
Department of Chemistry, Northwestern University
2145 Sheridan Road, Evanston, IL 60208 (USA)
Fax: (+1) 847-491-1009
E-mail: stoddart@northwestern.edu
Homepage: http://stoddart.northwestern.edu

[**] The research described here was supported by the National Science Foundation (NSF) in the United States under award CHE0924620.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201004304.

to the molecules, rendering (Figure 2) them rodlike. Specifically, we rationalized that by placing -$CH_2NH_2^+CH_2$- recognition sites approximately 3.5 Å apart from one another in the dumbbells, the macrocycles would be situated so as to optimize inter-ring [π···π] stacking interactions. We report, herein, the design, the synthesis, and characterization of some rigid [3]-, [4]-, [5]-, and [8]rotaxanes—namely **2R**·2PF_6, **3R**·3PF_6, **4R**·4PF_6, and **7R**·7PF_6.

The synthesis of the [3]rotaxane **2R**·2PF_6 is summarized in Figure 3a. The dialdehyde **5** and the diamine **6** were added to a solution of bisammonium salt **2D**·2PF_6 in CD_3CN. Within 5 min, **2R**·2PF_6 was formed in quantitative conversion according to ^{1}H NMR spectroscopy. The chemical shifts (Figure 3b) for the imine (H_c), pyridyl (H_a and H_b), and *ortho*-aryl (H_d–H_g) protons are in good agreement with those observed previously[15b] for a not dissimilar [2]rotaxane **1R**·PF_6. As expected, a single set of resonances in the ^{1}H NMR spectrum is observed for the two homotopic rings encircling the dumbbell.

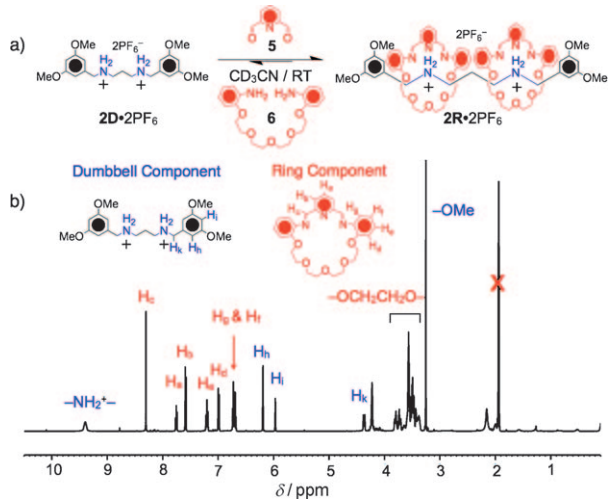

Figure 3. a) The template-directed synthesis of the [3]rotaxane **2R**·2PF_6, starting from **2D**·2PF_6, **5** and **6** employing Strategy B. b) The ^{1}H NMR spectrum (500 MHz, CD_3CN, 298 K) of the [3]rotaxane. The assignment of the resonances is assisted by partitioning the structural formula of **2R**$^{2+}$ into its separate dumbbell and ring components.

Electrospray ionization (ESI) mass spectrometry confirmed the constitution of the [3]rotaxane by the presence of an intense base peak at *m/z* 1471.6220, corresponding to [**2R**·PF_6]$^+$. Single crystals of the [3]rotaxane, suitable for X-ray crystallography, were grown by liquid–liquid diffusion of *i*Pr_2O into a solution of **2R**·2PF_6 in CH_2Cl_2. The solid-state structure of **2R**·2PF_6 (Figure 4a,b) reveals[17] that the three arenes in each of the two rings are in register with one another and that their average mean planes are separated by the [π···π] stacking distance of 3.5 Å. In addition, the conformation of **2R**·2PF_6 is stabilized[18] by four [N$^+$–H···N] hydrogen bonds and additional [π···π] stacking interactions between one of the terminal 3,5-dimethoxyphenyl rings on the dumbbell with one of the pyridyl rings in one of the macrocycles. This combination of noncovalent bonding interactions

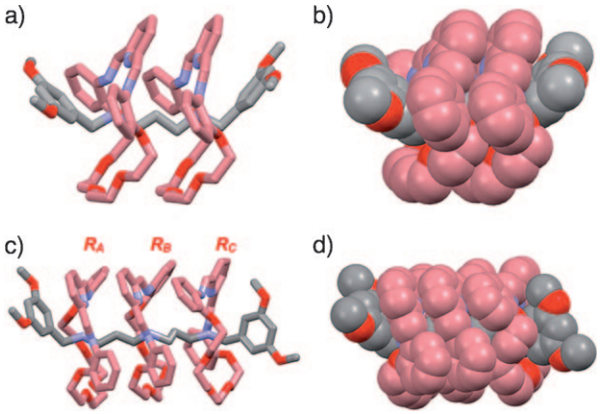

Figure 4. a) Stick and b) space-filling representations of the solid-state structure of **2R**$^{2+}$. The [N$^+$–H···N] distances range from 2.03 to 2.14 Å and have [N$^+$–H···N] angles of 172 and 174°. c) Stick and d) space-filling representations[21] of the solid-state structure of **3R**$^{3+}$. Hydrogen atoms and counterions have been omitted and discounted for clarity.

imposes[19] a linear, rigid conformation on the [3]rotaxane. This observation begs the question—do these noncovalent bonding interactions carry through to higher-order rotaxanes?

The [4]rotaxane **3R**·3PF_6 was prepared[20] (Figure 5a) in near quantitative conversion by adding **3D**·3PF_6 to 3 equivalents each of **5** and **6**. While the two outer rings are homotopic, they are constitutionally heterotopic with respect to the central ring, consistent with the 2:1 relative intensities in the ^{1}H NMR spectrum (Figure 5b) for the resonances arising from the heterotopic rings. The presence of sharp peaks at *m/z* 2149.8608 ([**3R**·2PF_6]$^+$), 1002.4507 ([**3R**·PF_6]$^{2+}$), and 619.9806 ([**3R**]$^{3+}$) in the ESI mass spectrum confirms the constitution of the rotaxane. Single crystals of the [4]rotaxane, suitable for X-ray crystallography, were grown by vapor diffusion of *tert*-butyl methyl ether into a solution of **3R**·3PF_6

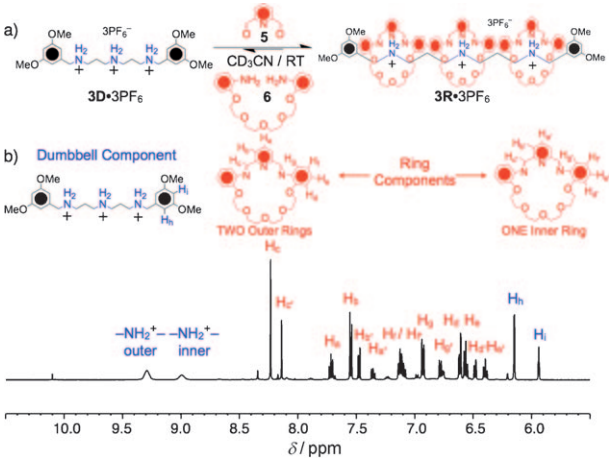

Figure 5. a) The template-directed synthesis of the [4]rotaxane **3R**·3PF_6 starting from **3D**·3PF_6, **5**, and **6**, and employing strategy B. b) The partial ^{1}H NMR spectrum (500 MHz, CD_3CN, 298 K) of the [4]rotaxane. The assignment of the resonances is assisted by partitioning the structural formula of **3R**$^{3+}$ into its separate dumbbell and ring—two outer and one inner—components.

in MeOH. In this case, the solid-state structure (Figure 4c,d) of $\mathbf{3R}^{3+}$ reveals[22] that the arenes in two of the macrocycles (R_A and R_B) are in register with one another—their average mean planes are separated by a distance of 3.5 Å—while the third macrocycle (R_C) is out of register with the other two by ca. 52°. This observation[23] is probably an artifact of crystal packing and does not change the rigid and rodlike *conformation* of the molecule. The [5]rotaxane, $\mathbf{4R}\cdot 4PF_6$, was also prepared in a similar fashion and characterized by ^{1}H NMR spectroscopy as well as by ESI mass spectrometry (see the Supporting Information). The spectroscopic evidence (see below) is consistent with this rotaxane having a rigid rodlike conformation.

In order to prepare higher-order rotaxanes, it has been necessary to develop syntheses of their dumbbell components using iterative reaction sequences. We illustrate this chemistry by outlining (Figure 6a) the synthesis of the dumbbell $\mathbf{7D}\cdot 7PF_6$ employing a single iteration beginning with the reductive amination of 3,5-dimethoxybenzaldehyde (**8**) and the diamine **9** to provide **10** which was subsequently Boc protected, affording the alcohol **11**. Swern oxidation afforded the aldehyde **12**, which was subjected to reductive amination with bis(3-aminopropyl)amine (**13**), followed by acid-mediated global deprotection of the amino groups and counterion exchange providing $\mathbf{7D}\cdot 7PF_6$. When this dumbbell was added to 7 equivalents each of **5** and **6**, the [8]rotaxane $\mathbf{7R}\cdot 7PF_6$ was obtained with near quantitative conversion. ESI mass spectrometry confirmed the constitutional identity of $\mathbf{7R}\cdot 7PF_6$ on account of the intense peaks at m/z 1524.2985 ($[\mathbf{7R}\cdot 4PF_6]^{3+}$), 1106.9836 ($[\mathbf{7R}\cdot 3PF_6]^{4+}$), and 856.5903 ($[\mathbf{7R}\cdot 2PF_6]^{5+}$). In the ^{1}H NMR spectrum (Figure 6b), there are four resonances in a 2:2:2:1 ratio, corresponding to the imine protons present in 1) the three homotopic pairs of heterotopic rings and 2) the central constitutionally heterotopic ring. The chemical shifts of the imine resonances move upfield as they become more shielded toward the center of the [8]rotaxane, i.e., the imine protons corresponding to ring R_A appear the furthest downfield while the imine protons corresponding to ring R_D appear the furthest upfield.

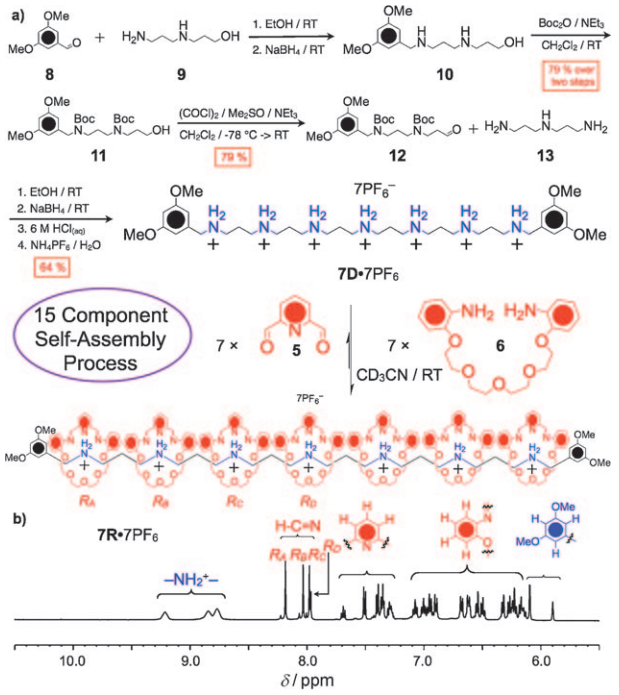

Figure 6. a) The synthesis of the dumbbell $\mathbf{7D}\cdot 7PF_6$ containing seven secondary dialkylammonium recognition sites which are employed under templation subsequently to assemble the [8]rotaxane under thermodynamic control leading into the template-directed synthesis of the [8]rotaxane $\mathbf{7R}\cdot 7PF_6$, starting from $\mathbf{7D}\cdot 7PF_6$, **5**, and **6**. b) The partial ^{1}H NMR spectrum (500 MHz, CD_3CN, 298 K) of the [8]rotaxane. The assignment of the resonances follows the practice established previously for the [3]- and [4]rotaxanes.

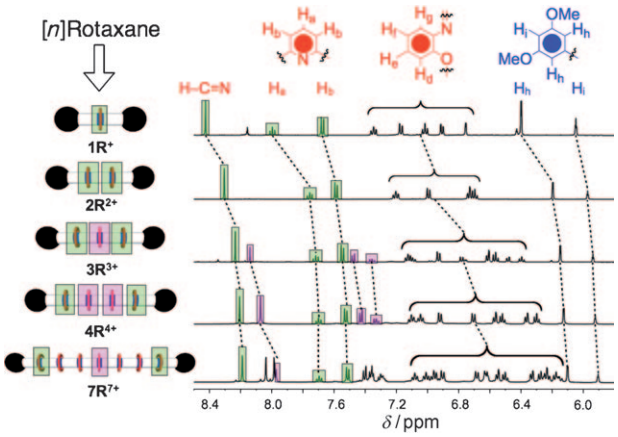

Figure 7. The partial ^{1}H NMR spectra (500 MHz, CD_3CN, 298 K), showing how the resonances for the imine and aromatic protons move to higher fields and—in the case of the dibenzo ring—fan out as more rings are added on going from the [2]- to the [3]- to the [4]- to the [5]- to the [8]rotaxane. This pattern of behavior is indicative of multiple [π···π] stacking interactions.

Conformational insight can be deduced from ^{1}H NMR spectroscopic data, in line with literature precedence[24] for other systems with efficient [π···π] stacking. In this present case, there is strong evidence (Figure 7) that the higher-order rotaxanes $\mathbf{4R}\cdot 4PF_6$ and $\mathbf{7R}\cdot 7PF_6$ are rodlike in solution. In moving from the [2]rotaxane to the higher-order rotaxanes, the resonances for the ring(s) that are nearest to the stoppers of the dumbbell relocate progressively upfield. For example, the imine proton in the [2]rotaxane, which resonates at $\delta =$ 8.42 ppm, moves upfield by $\delta = 0.12$, 0.28, 0.35, and 0.45 ppm, in turn, upon the addition of one (i.e., $\mathbf{2R}\cdot 2PF_6$), two (i.e., $\mathbf{3R}\cdot 3PF_6$), three (i.e., $\mathbf{4R}\cdot 4PF_6$), and six (i.e., $\mathbf{7R}\cdot 7PF_6$) rings. This upfield trend in chemical shifts is also observed for the pyridyl (H_a and H_b) and aryl (H_d–H_i) protons. These ^{1}H NMR shifts shed light on the overall conformation of these oligorotaxanes, in so far that as the number of macrocycles increases, the amount of [π···π] interactions (shielding) between the aromatic rings is more pronounced, accounting for the upfield shifts observed in the spectra. This observation is consistent with the stacking of aromatic rings, and strongly suggests that the conformation of these oligorotaxanes is rodlike in solution. Most importantly, this trend is not observed[12f] in the previously synthesized [3]-, [4]-, [5]-, [7]-, and [11]rotaxanes where [π···π] interactions between adjacent macrocycles are not possible.

In this research program, aimed at producing readily soluble, polycationic, monodisperse, rigid-rodlike polyrotaxanes for single-molecule investigations on surfaces and rheological studies in polar solvents, we have established proof-of-principle in terms of efficient, high-yielding, template-directed syntheses under thermodynamic control for [*n*]rotaxanes up to $n = 8$. The challenge, which we are tackling presently, is to extend the highly successful synthetic protocol, based on DCC and employing iterative reaction sequences, to make dumbbells with $(n-1)$ recognition sites from whence [*n*]rotaxanes, where *n* lies in the range 20–50, can be self-assembled by templation of multiple rings around each and every recognition site along the lengths of the dumbbells.

Experimental Section

In a typical procedure, the appropriate oligoammonium dumbbell compound (0.05 mmol, 1 equiv) was added to a solution of 2,6-pyridine-dicarboxaldehyde (**5**) (*n* equiv, *n* = number of ammonium recognition sites) and tetraethyleneglycol bis(2-aminophenyl)ether (**6**) (*n* equiv) in MeCN (1 mL) and stirred for 24 h at room temperature. Neat $i\mathrm{Pr_2O}$ was added dropwise to the reaction mixture until precipitation of the oligorotaxane was complete. The precipitate was collected by filtration, washed with $i\mathrm{Pr_2O}$, and air-dried to afford the oligorotaxane as a typically bright yellow powder.

2R·2 PF_6: Yield 93 %. ^{1}H NMR (CD_3CN, 500 MHz): $\delta = 9.40$ (br. s, 4H), 8.30 (s, 4H), 7.75 (t, $J = 7.8$ Hz, 2H), 7.59 (d, $J = 7.8$ Hz, 4H), 7.20 (t, $J = 8.0$ Hz, 4H), 6.99 (d, $J = 2$ Hz, 4H), 6.72 (t, $J = 8.0$ Hz, 4H), 6.70 (d, $J = 8.0$ Hz, 4H), 6.19 (d, $J = 2.2$ Hz, 4H), 5.97 (t, $J = 2.2$ Hz, 2H), 4.37 (t, $J = 6.8$ Hz, 4H), 4.24–4.21 (m, 8H), 3.82–3.78 (m, 4H), 3.74–3.70 (m, 4H), 3.58–3.37 (m, 20H), 3.25 (s, 12H), 1.9 ppm (br. s, 2H). ^{13}C NMR (CD_3CN, 125 MHz): $\delta = 161.3$, 160.0, 151.3, 151.1, 139.6, 138.8, 134.2, 129.6, 128.4, 121.0, 120.4, 112.1, 106.4, 100.2, 69.7, 69.6, 68.4, 67.8, 54.2, 50.8, 44.7, 23.1 ppm. HR-MS (ESI): *m*/*z* Calcd for $C_{75}H_{90}F_6N_8O_{14}P$ [**2R**·PF_6]$^+$: 1471.6217, found 1471.6220.

3R·3 PF_6: Yield 90 %. ^{1}H NMR (CD_3CN, 500 MHz): $\delta = 9.29$ (br. s, 4H), 8.99 (br. s, 2H), 8.23 (s, 4H), 8.14 (s, 2H), 7.72 (t, $J = 7.7$ Hz, 2H), 7.54 (d, $J = 7.7$ Hz, 4H), 7.47 (d, $J = 7.7$ Hz, 2H), 7.36, (t, $J = 7.7$ Hz, 1H), 7.14–7.08 (m, 6H), 6.92 (d, $J = 8.3$ Hz, 4H), 6.78 (d, $J = 8.3$ Hz, 2H), 6.61 (d, $J = 8.3$ Hz, 4H), 6.56 (t, $J = 8.3$ Hz, 4H), 6.48 (d, $J = 8.3$ Hz, 2H), 6.39 (t, $J = 8.3$ Hz, 2H), 6.15 (d, $J = 2.3$ Hz, 4H), 5.94 (t, $J = 2.3$ Hz, 2H), 4.22 (t, $J = 7.0$ Hz, 4H), 4.15–4.13 (m, 8H), 3.89 (t, $J = 3.9$ Hz, 4H), 3.76–3.32 (m, 36H), 3.33 (br. s, 4H), 3.18 (br. s, 4H), 3.26 (s, 12H), 1.72 ppm (br. s, 4H). ^{13}C NMR: see SI. HR-MS (ESI): *m*/*z* Calcd for $C_{105}H_{127}F_{12}N_{12}O_{19}P_2$ [**3R**·2 PF_6]$^+$: 2149.8622, found 2149.8608; Calcd for $C_{105}H_{127}F_6N_{12}O_{19}P_1$ [**3R**·PF_6]$^{2+}$: 1002.4490, found 1002.4507; Calcd for $C_{105}H_{127}N_{12}O_{19}$ [**3R**]$^{3+}$: 619.9780, found 619.9806.

4R·4 PF_6: Yield 88 %. ^{1}H NMR (CD_3CN, 500 MHz): $\delta = 9.25$ (br. s, 4H), 8.90 (br. s, 4H), 8.20 (s, 4H), 8.07 (s, 4H), 7.69 (t, $J = 7.7$ Hz, 2H), 7.52 (d, $J = 7.7$ Hz, 4H), 7.42 (d, $J = 7.7$ Hz, 4H), 7.32 (t, $J = 7.7$ Hz, 2H), 7.10 (t, $J = 8.4$ Hz, 4H), 7.04 (t, $J = 8.4$ Hz, 4H), 6.92 (d, $J = 8.4$ Hz, 4H), 6.70 (d, $J = 8.4$ Hz, 4H), 6.56 (d, $J = 7.3$ Hz, 4H), 6.51 (t, $J = 7.3$ Hz, 4H), 6.36 (t, $J = 7.3$ Hz, 4H), 6.29 (t, $J = 7.3$ Hz, 4H), 6.12 (d, $J = 1.9$ Hz, 4H), 5.91 (t, $J = 1.9$ Hz, 2H), 4.18–4.08 (m, 12H), 3.81–3.72 (m, 8H), 3.67 (br. s, 8H), 3.55–3.52 (m, 15H), 3.42–3.32 (m, 30H), 3.27 (s, 12H), 3.10–3.05 (m, 7H), 1.65 (br. s, 4H), 1.47 ppm (br. s, 2H). ^{13}C NMR: see SI. HR-MS (ESI): *m*/*z* Calcd for $C_{135}H_{164}F_{12}N_{16}O_{24}P_2$ [**4R**·2 PF_6]$^{2+}$: 1341.5689, found 1341.5625; Calcd for $C_{135}H_{164}F_6N_{16}O_{24}P_1$ [**4R**·PF_6]$^{3+}$: 846.0577, found 846.0558.

7R·7 PF_6: Yield 94 %. see Supporting Information for ^{1}H and ^{13}C spectroscopic data. HR-MS (ESI): *m*/*z* Calcd for $C_{225}H_{275}F_{24}N_{28}O_{39}P_4$ [**7R**·4 PF_6]$^{3+}$: 1524.2982, found 1524.2985; Calcd for $C_{225}H_{275}F_{18}N_{28}O_{39}P_3$ [**7R**·3 PF_6]$^{4+}$: 1106.9825, found 1106.9836; Calcd. for $C_{225}H_{275}F_{12}N_{28}O_{39}P_2$ [**7R**·2 PF_6]$^{5+}$: 856.5930, found 856.5903.

Received: July 14, 2010
Published online: August 30, 2010

Keywords: dynamic covalent chemistry · mechanically interlocked molecules · molecular recognition · noncovalent bonding interactions · self-assembly

[1] a) C. P. Collier, G. Mattersteig, E. W. Wong, Y. Luo, K. Beverly, J. Sampaio, F. M. Raymo, J. F. Stoddart, J. R. Heath, *Science* **2000**, *289*, 1172–1175; b) J. E. Green, J. W. Choi, A. Boukai, Y. Bunimovich, E. Johnston-Halperin, E. DeIonno, Y. Luo, B. A. Sheriff, K. Xu, Y. S. Shin, H.-R. Tseng, J. F. Stoddart, J. R. Heath, *Nature* **2007**, *445*, 414–417; c) J. R. Heath, *Annu. Rev. Mater. Res.* **2009**, *39*, 1–23; d) S. J. van der Molen, P. Liljeroth, *J. Phys. Condens. Matter* **2010**, *22*, 133001–133030.

[2] a) Y. Liu, A. H. Flood, P. A. Bonvallet, S. A. Vignon, B. H. Northrop, H.-R. Tseng, J. O. Jeppesen, T. J. Huang, B. Brough, M. Baller, S. Magonov, S. D. Solares, W. A. Goddard, C.-M. Ho, J. F. Stoddart, *J. Am. Chem. Soc.* **2005**, *127*, 9745–9759; b) B. K. Juluri, A. S. Kumar, Y. Liu, T. Ye, Y.-W. Yang, A. H. Flood, L. Fang, J. F. Stoddart, P. S. Weiss, T. J. Huang, *ACS Nano* **2009**, *3*, 291–300.

[3] a) K. Patel, S. Angelos, W. R. Dichtel, A. Coskun, Y.-W. Yang, J. I. Zink, J. F. Stoddart, *J. Am. Chem. Soc.* **2008**, *130*, 2382–2383; b) K. K. Cotí, M. E. Belowich, M. Liong, M. W. Ambrogio, Y. A. Lau, H. A. Khatib, J. I. Zink, N. M. Khashab, J. F. Stoddart, *Nanoscale* **2009**, *1*, 16–39; c) A. Schlossbauer, S. Warncke, P. M. E. Gramlich, J. Kecht, A. Manetto, T. Carell, T. Bein, *Angew. Chem.* **2010**, *122*, 4842–4845; *Angew. Chem. Int. Ed.* **2010**, *49*, 4734–4737; d) R. Klajn, J. F. Stoddart, B. A. Grzybowski, *Chem. Soc. Rev.* **2010**, *39*, 2203–2237.

[4] a) P. A. Brady, R. P. Bonar-Law, S. J. Rowan, C. J. Suckling, J. K. M. Sanders, *Chem. Commun.* **1996**, 319–320; b) P. A. Brady, J. K. M. Sanders, *Chem. Soc. Rev.* **1997**, *26*, 327–336; c) J.-M. Lehn, *Chem. Eur. J.* **1999**, *5*, 2455–2463; d) J. K. M. Sanders, *Pure Appl. Chem.* **2000**, *72*, 2265–2274; e) L. M. Greig, D. Philp, *Chem. Soc. Rev.* **2001**, *30*, 287–302; f) R. L. E. Furlan, S. Otto, J. K. M. Sanders, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 4801–4804; g) S. J. Rowan, S. J. Cantrill, G. R. L. Cousins, J. K. M. Sanders, J. F. Stoddart, *Angew. Chem.* **2002**, *114*, 938–993; *Angew. Chem. Int. Ed.* **2002**, *41*, 898–952; h) P. T. Corbett, J. Leclaire, L. Vial, K. R. West, J.-L. Wietor, J. K. M. Sanders, S. Otto, *Chem. Rev.* **2006**, *106*, 3652–3711; i) J.-M. Lehn, *Chem. Soc. Rev.* **2007**, *36*, 151–160; j) A. Granzhan, T. Riis-Johannessen, R. Scopelliti, K. Severin, *Angew. Chem.* **2010**, *122*, 5647–5650; *Angew. Chem. Int. Ed.* **2010**, *49*, 5515–5518.

[5] a) I. T. Harrison, *J. Chem. Soc. Chem. Commun.* **1972**, 231–232; b) S. J. Cantrill, S. J. Rowan, J. F. Stoddart, *Org. Lett.* **1999**, *1*, 1363–1366; c) Y. Furusho, T. Hasegawa, A. Tsuboi, N. Kihara, T. Takata, *Chem. Lett.* **2000**, 18–19; d) A.-M. Fuller, D. A. Leigh, P. J. Lusby, I. D. H. Oswald, S. Parsons, D. B. Walker, *Angew. Chem.* **2004**, *116*, 4004–4008; *Angew. Chem. Int. Ed.* **2004**, *43*, 3914–3918; e) Z. Xue, M. F. Mayer, *J. Am. Chem. Soc.* **2010**, *132*, 3274–3276.

[6] a) M. Fujita, F. Ibukuro, H. Hagihara, K. Ogura, *Nature* **1994**, *367*, 720–723; b) B. Mohr, M. Weck, J.-P. Sauvage, R. H. Grubbs, *Angew. Chem.* **1997**, *109*, 1365–1367; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 1308–1310; c) D. G. Hamilton, N. Feeder, S. J. Teat, J. K. M. Sanders, *New J. Chem.* **1998**, *22*, 1019–1021; d) T. J. Kidd, D. A. Leigh, A. J. Wilson, *J. Am. Chem. Soc.* **1999**, *121*, 1599–1600; e) G. Kaiser, T. Jarrosson, S. Otto, Y.-F Ng, A. D. Bond, J. K. M. Sanders, *Angew. Chem.* **2004**, *116*, 1993–

1996; *Angew. Chem. Int. Ed.* **2004**, *43*, 1959 – 1962; f) O. Š. Miljanić, J. F. Stoddart, *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 12966 – 12970; g) M. A. Olson, A. Coskun, L. Fang, A. N. Basuray, J. F. Stoddart, *Angew. Chem.* **2010**, *122*, 3219 – 3224; *Angew. Chem. Int. Ed.* **2010**, *49*, 3151 – 3156.

[7] A. R. Williams, B. H. Northrop, T. Chang, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem.* **2006**, *118*, 6817 – 6821; *Angew. Chem. Int. Ed.* **2006**, *45*, 6665 – 6669.

[8] a) C. Dietrich-Buchecker, G. Rapenne, J.-P. Sauvage, *Chem. Commun.* **1997**, 2053 – 2054; b) L.-E. Perret-Aebi, A. von Zelewsky, C. Dietrich-Buchecker, J.-P. Sauvage, *Angew. Chem.* **2004**, *116*, 4582 – 4585; *Angew. Chem. Int. Ed.* **2004**, *43*, 4482 – 4485; c) J. Guo, P. C. Mayers, G. A. Breault, C. A. Hunter, *Nat. Chem.* **2010**, *2*, 218 – 222.

[9] a) K. S. Chichak, S. J. Cantrill, A. R. Pearse, S.-H. Chiu, G. W. V. Cave, J. L. Atwood, J. F. Stoddart, *Science* **2004**, *304*, 1308 – 1312; b) K. S. Chichak, A. J. Peters, S. J. Cantrill, J. F. Stoddart, *J. Org. Chem.* **2005**, *70*, 7956 – 7962; c) C. D. Meyer, R. S. Forgan, K. S. Chichak, A. J. Peters, N. Tangchaivang, G. W. V. Cave, S. I. Khan, S. J. Cantrill, J. F. Stoddart, *Chem. Eur. J.* **2010**, in press.

[10] C. D. Pentecost, K. S. Chichak, A. J. Peters, G. W. V. Cave, S. J. Cantrill, J. F. Stoddart, *Angew. Chem.* **2007**, *119*, 222 – 226; *Angew. Chem. Int. Ed.* **2007**, *46*, 218 – 222.

[11] a) A. Harada, J. Li, M. Kamachi, *Nature* **1992**, *356*, 325 – 327; b) C. Gong, Q. Ji, C. Subramaniam, H. W. Gibson, *Macromolecules* **1998**, *31*, 1814 – 1818; c) F. M. Raymo, J. F. Stoddart, *Chem. Rev.* **1999**, *99*, 1643 – 1663; d) A. Harada, A. Hashidzume, H. Yamaguchi, Y. Takashima, *Chem. Rev.* **2009**, *109*, 5974 – 6023.

[12] a) J. A. Bravo, F. M. Raymo, J. F. Stoddart, A. J. P. White, D. J. Williams, *Eur. J. Org. Chem.* **1998**, 2565 – 2571; b) C. Seel, F. Vögtle, *Chem. Eur. J.* **2000**, *6*, 21 – 24; c) ref. [5d]; d) F. Aricó, J. D. Badjić, S. J. Cantrill, A. H. Flood, K. C.-F. Leung, Y. Liu, J. F. Stoddart, *Top. Curr. Chem.* **2005**, *249*, 203 – 259; e) N. N. P. Moonen, A. H. Flood, J. M. Fernández, J. F. Stoddart, *Top. Curr. Chem.* **2005**, *262*, 99 – 132; f) J. Wu, K. C.-F. Leung, J. F. Stoddart, *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 17266 – 17271.

[13] a) J. A. Wisner, P. D. Beer, M. G. B. Drew, M. R. Sambrook, *J. Am. Chem. Soc.* **2002**, *124*, 12469 – 12476; b) A. F. M. Kilbinger, S. J. Cantrill, A. W. Waltman, M. W. Day, R. H. Grubbs, *Angew. Chem.* **2003**, *115*, 3403 – 3407; *Angew. Chem. Int. Ed.* **2003**, *42*, 3281 – 3285; c) F. Aricó, P. Mobian, J.-M. Kern, J.-P. Sauvage, *Org. Lett.* **2003**, *5*, 1887 – 1890; d) J. D. Badjić, S. J. Cantrill, R. H. Grubbs, E. N. Guidry, R. Orenes, J. F. Stoddart, *Angew. Chem.* **2004**, *116*, 3335 – 3340; *Angew. Chem. Int. Ed.* **2004**, *43*, 3273 – 3278; e) E. N. Guidry, S. J. Cantrill, J. F. Stoddart, R. H. Grubbs, *Org. Lett.* **2005**, *7*, 2129 – 2132; f) S. J. Cantrill, R. H. Grubbs, D. Lanari, K. C.-F. Leung, A. Nelson, K. G. Poulin-Kerstien, S. P. Smidt, J. F. Stoddart, D. A. Tirrell, *Org. Lett.* **2005**, *7*, 4213 – 4216; g) H. Hou, K. C.-F. Leung, D. Lanari, A. Nelson, J. F. Stoddart, R. H. Grubbs, *J. Am. Chem. Soc.* **2006**, *128*, 15358 – 15359; h) E. N. Guidry, J. Li, J. F. Stoddart, R. H. Grubbs, *J. Am. Chem. Soc.* **2007**, *129*, 8944 – 8945; i) P. G. Clark, M. W. Day, R. H. Grubbs, *J. Am. Chem. Soc.* **2009**, *131*, 13631 – 13633.

[14] a) A. G. Kolchinski, N. W. Alcock, R. A. Roesner, D. H. Busch, *Chem. Commun.* **1998**, 1437 – 1438; b) T. Oku, T. Furusho, T. Takata, *J. Polym. Sci. Part A* **2003**, *41*, 119 – 123; c) Y. Furusho, T. Oku, G. A. Rajkumar, T. Takata, *Chem. Lett.* **2004**, *33*, 52 – 53; d) H. Y. Au-Yeung, G. D. Pantoş, J. K. M. Sanders, *Angew. Chem.* **2010**, *122*, 5459 – 5462; *Angew. Chem. Int. Ed.* **2010**, *49*, 5331 – 5334.

[15] a) S. J. Rowan, J. F. Stoddart, *Org. Lett.* **1999**, *1*, 1913 – 1916; b) P. T. Glink, A. I. Oliva, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem.* **2001**, *113*, 1922 – 1927; *Angew. Chem. Int. Ed.* **2001**, *40*, 1870 – 1875; c) M. Horn, J. Ihringer, P. T. Glink, J. F. Stoddart, *Chem. Eur. J.* **2003**, *9*, 4046 – 4054; d) F. Aricó, T. Chang, S. J. Cantrill, S. I. Khan, J. F. Stoddart, *Chem. Eur. J.* **2005**, *11*, 4655 – 4666; e) C. D. Meyer, C. S. Joiner, J. F. Stoddart, *Chem. Soc. Rev.* **2007**, *36*, 1705 – 1723; f) P. C. Haussmann, S. I. Khan, J. F. Stoddart, *J. Org. Chem.* **2007**, *72*, 6708 – 6713; g) T. Umehara, H. Kawai, K. Fujiwara, T. Suzuki, *J. Am. Chem. Soc.* **2008**, *130*, 13981 – 13988; h) L. M. Klivansky, G. Koshkakaryan, D. Cao, Y. Liu, *Angew. Chem.* **2009**, *121*, 4249 – 4253; *Angew. Chem. Int. Ed.* **2009**, *48*, 4185 – 4189; i) P. C. Haussmann, J. F. Stoddart, *Chem. Rec.* **2009**, *9*, 136 – 154; j) J. Yin, S. Dasgupta, J. Wu, *Org. Lett.* **2010**, *12*, 1712 – 1715.

[16] L. Fang, M. A. Olson, D. Benítez, E. Tkatchouk, W. A. Goddard, J. F. Stoddart, *Chem. Soc. Rev.* **2010**, *39*, 17 – 29.

[17] Crystal data for **2R**·2PF$_6$. $C_{75}H_{90}F_{12}N_8O_{14}P_2{\cdot}CH_2Cl_2{\cdot}(C_3H_7)_2O$. $M = 1804.59$, space group $P1$, triclinic, $a = 13.4795(5)$, $b = 14.5068(4)$, $c = 24.8176(7)$ Å, $\alpha = 85.849(2)°$, $\beta = 88.703(2)°$, $\gamma = 62.846(2)°$, $V = 4306.4(2)$ Å^3, $Z = 2$, Calculated density = 1.392 g cm^{-3}, $\mu = 1.839$ mm^{-1}, 13912 reflections collected, 13912 observed independent reflections ($R_{int} = 0.0000$) gave $R = 0.0601$ for $I > 2\sigma(I)$ and wR_2 was 0.1616.

[18] There are intramolecular [C–H···π] interactions in the crystal lattice between the 3,5-dimethoxyphenyl unit of one molecule and the 3,5-dimethoxyphenyl unit of the adjacent molecule.

[19] For an example of pseudorotaxanes stabilized by [π···π] interactions between the aromatic ring of one macrocycle with the aromatic ring of the dumbbell component see: S. J. Cantrill, A. R. Pease, J. F. Stoddart, *J. Chem. Soc. Dalton Trans.* **2000**, 3715 – 3734.

[20] 2,6-Pyridinedicarboxaldehyde (**5**) exists in solution in < 7 % as a result of error in stoichiometry. It does not exist as a result of dissociation from **3R**·3PF$_6$ because it can be removed by further purification.

[21] The [N$^+$–H···N] distances are not provided in the case of **3R**$^{3+}$ as a result of the dumbbell component being disordered in the crystal lattice.

[22] Crystal data for **3R**·3PF$_6$. $C_{105}H_{127}F_{18}N_{12}O_{19}P_3$. $M = 2296.10$, space group $P2_1/n$, monoclinic, $a = 16.3196(4)$, $b = 31.1755(7)$, $c = 22.7396(5)$ Å, $\alpha = 90.000(2)°$, $\beta = 95.673(2)°$, $\gamma = 90.000(2)°$, $V = 11512.6(5)$ Å^3, $Z = 4$, Calculated density = 1.325 g cm^{-3}, $\mu = 1.320$ mm^{-1}, 78337 reflections collected, 18089 observed independent reflections ($R_{int} = 0.0765$) gave $R = 0.0840$ for $I > 2\sigma(I)$ and wR_2 was 0.2296.

[23] R_C is twisted by approximately 52° with respect to the other two macrocycles (R_A and R_B) thus forming only two sets of [π···π] interactions with R_B. This phenomenon is most likely a result of [π···π] interactions between one arene of R_C with a 3,5-dimethoxyphenyl ring of the adjacent molecule in the crystal lattice.

[24] a) Y. Yamauchi, M. Yoshizawa, M. Fujita, *J. Am. Chem. Soc.* **2008**, *130*, 5832 – 5833; b) Y. Yamauchi, M. Yoshizawa, M. Akita, M. Fujita, *J. Am. Chem. Soc.* **2010**, *132*, 960 – 966.

