JOC Article

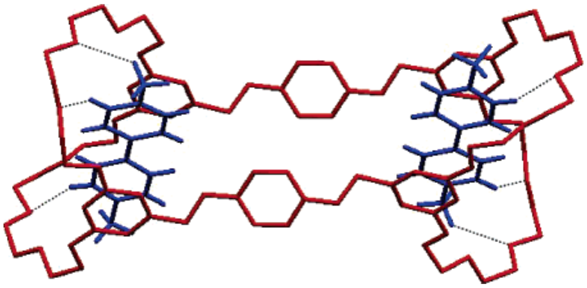
Synthesis of a Symmetric Cylindrical Bis(crown ether) Host and Its Complexation with Paraquat

Feihe Huang,[†] Lev N. Zakharov,[‡] Arnold L. Rheingold,[‡] Mehdi Ashraf-Khorassani,[†] and
Harry W. Gibson*[,†]

Department of Chemistry, Virginia Polytechnic Institute and State University,
Blacksburg, Virginia 24061-0212, Department of Chemistry and Biochemistry, University of California,
San Diego, La Jolla, California 92093-0358

hwgibson@vt.edu

Received October 25, 2004



The first cylindrical host for paraquat derivatives was prepared and characterized by X-ray analysis. Its complex with paraquat has 1:2 stoichiometry. The complexation is statistical and strong as shown by proton NMR characterization, electrospray mass spectrometry, and X-ray analysis.

Introduction

Host–guest chemistry has been a topic of great interest for a long time.[1] Paraquat derivatives (*N*,*N*′-dialkyl-4,4′-bipyridinium salts), viologens, are some of the most common guests in this field.[2] Both monocyclic[3] and bicyclic polyethers[4] have been used as hosts for them in the fabrication of numerous host–guest complexes. Cylindrical tricyclic polyethers, formed by connecting two macrocycles together through two bridges, have different topological features.[5] Most of the previously reported cylindrical polyethers were designed and prepared for efficient binding of metal ions[6] and diammonium salts.[7]

---

* To whom correspondence should be addressed. Fax: 540-231-8517.

[†] Virginia Polytechnic Institute and State University.

[‡] University of California.

(1) Vögtle, F. *Supramolecular Chemistry*; John Wiley and Sons: New York, 1991. Cram, D. J.; Cram, J. M. *Container Molecules and Their Guests*; Royal Society of Chemistry, Cambridge, UK, 1994. Lehn, J.-M. *Supramolecular Chemistry*; VCH Publishers: New York, 1995. *Comprehensive Supramolecular Chemistry*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Vögtle, F., Exec. Eds.; Pergamon Press: New York, 1996. Ozin, G. A. *Chem. Commun.* **2000**, *6*, 419–432. Prins, L. J.; Reinhoudt, D. N.; Timmerman, P. *Angew. Chem., Int. Ed.* **2001**, *40,* 2382–2426. Beer, P. D.; Gale, P. A. *Angew. Chem., Int. Ed.* **2001**, *40,* 486-516. For recent work, see: Sijbesma, R. P.; Meijer, E. W. *Chem. Commun.* **2003**, 5–16. Leigh, D. A.; Wong, J. K. Y.; Dehez, F.; Zerbetto, F. *Nature* **2003**, *424*, 174–179. Cavallini, M.; Biscarini, F.; Leon, S.; Zerbetto, F.; Bottari, G.; Leigh, D. A. *Science* **2003**, *299*, 531. Scarso, A.; Rebek, J., Jr. *J. Am. Chem. Soc.* **2004**, *126*, 8956–8960.

(2) *Molecular Catenanes, Rotaxanes and Knots*; Sauvage, J.-P., Dietrich-Buchecker, C. O., Eds.; Wiley-VCH: Weinheim, 1999. Raymo, F. M.; Stoddart, J. F. *Chem. Rev.* **1999**, *99*, 1643–1664. *Supramolecular Chemistry*; Steed, J. W., Atwood, J. L., Eds.; J. Wiley and Sons: New York, 2000. Mahan E.; Gibson H. W. In *Cyclic Polymers*, 2nd ed.; Semlyen, A. J., Ed.; Kluwer Publishers: Dordrecht, 2000; pp 415–560. Panova, I. G.; Topchieva, I. N. *Russ. Chem. Rev.* **2001**, *70*, 23–44.

(3) Monocylic polyethers are also called crown ethers. For recent publications on crown ether/paraquat complexes, see: (a) Jones, J. W.; Zhakarov, L. V.; Rheingold, A. L.; Gibson, H. W. *J. Am. Chem. Soc.* **2002**, *124,* 13378–13379. (b) Huang, F.; Fronczek, F. R.; Gibson, H. W. *Chem. Commun*. **2003**, 1480–1481. (c) Long, B.; Nikitin, K.; Fitzmaurice, D. *J. Am. Chem. Soc.* **2003**, *125*, 15490–15498. (d) Badjic, J. D.; Balzani, V.; Credi, A.; Silvi, S.; Stoddart, J. F. *Science* **2004**, *303*, 1845–1849. (e) Badjic, J. D.; Cantrill, S. J.; Stoddart, J. F. *J. Am. Chem. Soc.* **2004**, *126*, 2288–2289.

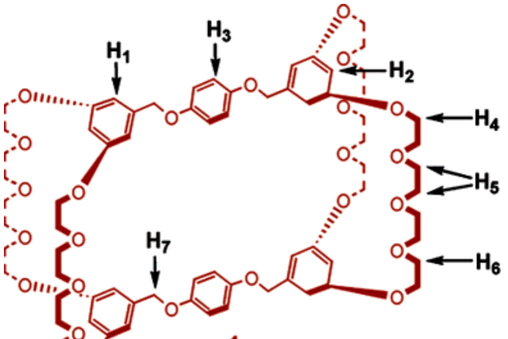
(4) Bicylic hosts are also called cryptands. For recent publications on cryptand/paraquat complexes, see: (a) Gunter, M. J.; Jeynes, T. P.; Johnston, M. R.; Turner, P.; Chen, Z. *J. Chem. Soc., Perkin Trans. 1* **1998**, 1945–1957. (b) Elemans, J. A. A. W.; Claase, M. B.; Aarts, P. P. M.; Rowan, A. E.; Schenning, A. P. H. J.; Nolte, R. J. M. *J. Org. Chem.* **1999**, *64*, 7009–7016. (c) Bryant, W. S.; Jones, J. W.; Mason, P. E.; Guzei, I. A.; Rheingold, A. L.; Nagvekar, D. S.; Gibson, H. W. *Org. Lett.* **1999**, *1*, 1001–1004. (d) Huang, F.; Fronczek, F. R.; Gibson, H. W. *J. Am. Chem. Soc.* **2003**, *125*, 9272–9273. (e) Huang, F.; Gibson, H. W.; Bryant, W. S.; Nagvekar, D. S.; Fronczek, F. R. *J. Am. Chem. Soc.* **2003**, *125,* 9367–9371.

(5) An, H.; Bradshaw, J. S.; Izatt, R. M. *Chem. Rev.* **1992**, *92*, 543–572.

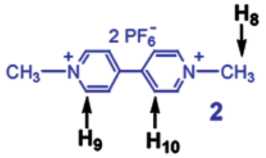
(6) Anelli, P. L.; Montanari, F.; Quici, S. Ciani, G.; Sironi, A. *J. Org. Chem.* **1988**, *53*, 5292–5298. An, H.; Bradshaw, J. S.; Krakowiak, K. E.; Zhu, C.; Dalley, N. K.; Izatt, R. M. *J. Org. Chem.* **1992**, *57*, 4998–5005. An, H.; Bradshaw, J. S.; Krakowiak, K. E.; Tarbet, B. J.; Dalley, N. K.; Kou, X.; Zhu, C.; Izatt, R. M. *J. Org. Chem.* **1993**, *58*, 7694–7699.

10.1021/jo048111u CCC: $30.25 © 2005 American Chemical Society

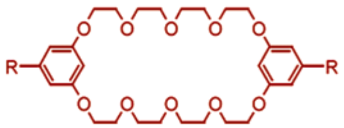
Here we report the synthesis of the first cylindrical host (**1**) for paraquat derivatives and its complexation with paraquat (**2**). This new symmetric bis(crown ether) host is homoditopic so it can be used in the construction of supramolecular polymers. The inclusion of two or more guest molecules within a molecular host is attractive because it provides unique opportunities to study new forms of stereoisomerism, bimolecular reactions, and molecular recognition in microenvironments,[8] so it is valuable to study the complexation between **1** and **2**.



1



2



3

a. R = CH_2Br; b. R = CH_2OPhOH; c. R = H; d. R = CH_2OH

Results and Discussion

Design, Synthesis, and X-ray Analysis of the Symmetric Cylindrical Bis(crown ether) Host 1. The design of **1** was inspired by the formation of taco complexes between bis(*m*-phenylene)-32-crown-10 derivatives (**3**) and paraquat derivatives.[3a,b,4c] We reasoned that **1** should be able to bind two paraquats strongly due to the preorganization of its two crown ether units. The first step for making **1** was the preparation of **3b** in 83% yield by the reaction of **3a**[9] with excess hydroquinone. Then equimolar **3a** and **3b** reacted under pseudo-high dilution conditions to afford **1** in 32% yield. As shown by its X-ray structure (Figure 1),[10] in the solid state **1** has a collapsed central cavity with nearly parallel pairs of aromatic rings. The dihedral angles/centroid−centroid distances between the two phenylene rings of each crown unit and between the hydroquinone rings are 1.2°/4.85 Å and 4.2°/4.97 Å, respectively.

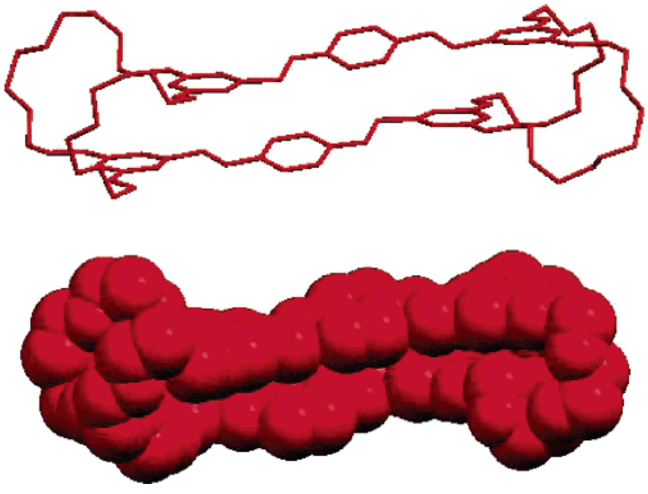


FIGURE 1. Two views of the X-ray structure of **1**. Two solvent molecules and hydrogens have been omitted for clarity.

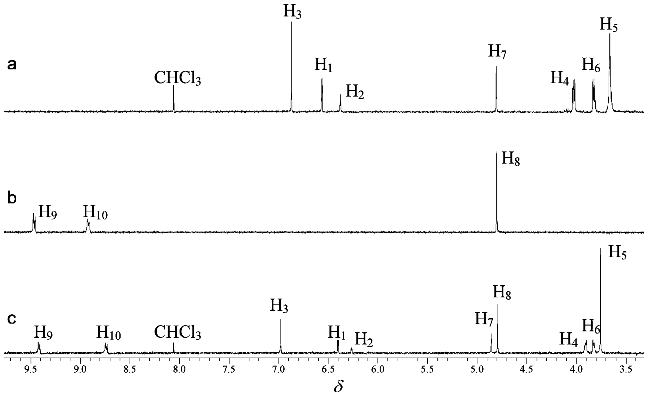


FIGURE 2. Partial ^1H NMR spectra (400 MHz, acetone-d_6, 22 °C) of (a, top) cylindrical bis(crown ether) **1**, (b, middle) paraquat **2**, and (c, bottom) a solution of 0.670 mM **1** and 1.33 mM **2**.

Proton NMR Study of Complexation between Bis(crown ether) Host 1 and Paraquat 2. Solutions of **1** and **2** are yellow due to charge transfer between the electron-rich aromatic rings of host **1** and the electron-poor pyridinium rings of guest **2**. ^1H NMR spectroscopy (Figure 2) indicated that exchange was fast and complexation was strong on the basis of the significant upfield shifts of the bipyridinium protons (H_9 and H_{10}) of **2**, the aromatic protons (H_1 and H_2), and α-ethyleneoxy protons (H_4) of **1** and the downfield shifts of protons H_3 and H_5 of **1**. As we expected, **1** forms a 1:2 complex with **2** in solution as shown by a mole ratio plot[11] (Figure 3) using the proton NMR data of H_1 on **1**.

---

(7) Chapoteau, E.; Czech, B. P.; Kumar, A.; Pose, A. *J. Inclusion Phenom.* **1988**, *6*, 41−47. Fages, F.; Desvergne, J.-P.; Kampke, K.; Bouas-Laurent, H.; Lehn, J.-M.; Meyer, M.; Albrecht-Gary, A. M. *J. Am. Chem. Soc.* **1993**, *115*, 3658−3664. Ballardini, R.; Balzani, V.; Credi, A.; Gandolfi, M. T.; Kotzyba-Hibert, F.; Lehn, J.-M.; Prodi, L. *J. Am. Chem. Soc.* **1994**, *116*, 5741−5746.

(8) Kim, H.-J.; Heo, J.; Jeon, W. S.; Lee, E.; Kim, J.; Sakamoto, S.; Yamaguchi, K.; Kim, K. *Angew. Chem., Int. Ed.* **2001**, *40*, 1526−1529 and references therein.

(9) Gibson, H. W.; Nagvekar, D. S. *Can. J. Chem.* **1997**, *75*, 1375−1384.

(10) Crystal data of $\mathbf{1}\cdot(C_3H_6O)_2$: block, colorless, 0.32 × 0.22 × 0.14 mm^3, $C_{78}H_{104}O_{26}$, FW 1457.61, monoclinic, space group $P2_1/c$, a = 17.5307(15) Å, b = 17.4709(15) Å, c = 25.626(2) Å, β = 105.3810(10)°, V = 7568(1) $Å^3$, Z = 4, D_c = 1.279 g cm^{-3}, T = 100(2) K, μ = 0.96 cm^{-1}, 17 024 independent reflections (R_{int} = 0.0351), 930 parameters, R1 = 0.0622, wR2 = 0.1517 [$I > 2\sigma(I)$], and GoF = 1.071.

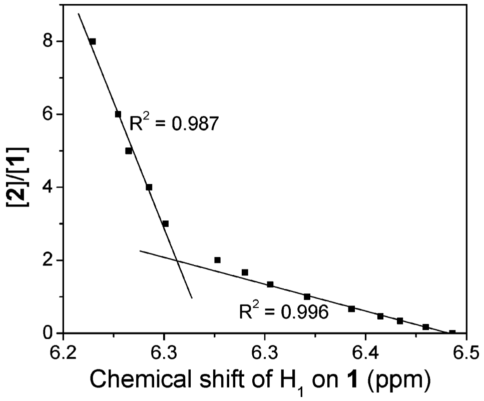


FIGURE 3. Mole ratio plot for the complexation between **1** and **2** in acetone-d_6/chloroform-*d* (5:1).

Scatchard Plots for Complexation between Bis(crown ether) Host 1 and Paraquat 2. To study the relationship between the two crown ether binding sites of **1** during the complexation with **2**, proton NMR characterizations were done on a series of acetone/chloroform (5:1) solutions for which the initial concentration of **1** was kept constant at 0.500 mM while the initial concentration of **2** was systematically varied. On the basis of these data, the extent of complexation, *p*, of crown ether units was determined[12] and a Scatchard plot[13] was made (Figure 4a). The linear nature of this plot demonstrated that the complexation between **1** and **2** is statistical, i.e., the two crown ether binding sites behave independently. From the intercept and the slope of the plot the average association constant[14] (K_{av}) is 4.0 (±0.4) × 10^3 M^{-1}. The same study was done in a more polar solvent, acetone, and the corresponding value of K_{av} decreased to 1.7 (±0.2) × 10^3 M^{-1} (Figure 4b).[14] However, this latter value represents a 3-fold increase from the value of the association constant (K_a = 5.7 × 10^2 M^{-1}) for the complexation between the simple crown ether **3c** and **2** in acetone,[4e] but it is much lower than the association constants for the complexation between cryptands and **2**.[4c,e] This is understandable considering that the crown ether units in **1** do not have as many binding sites as the cryptands.

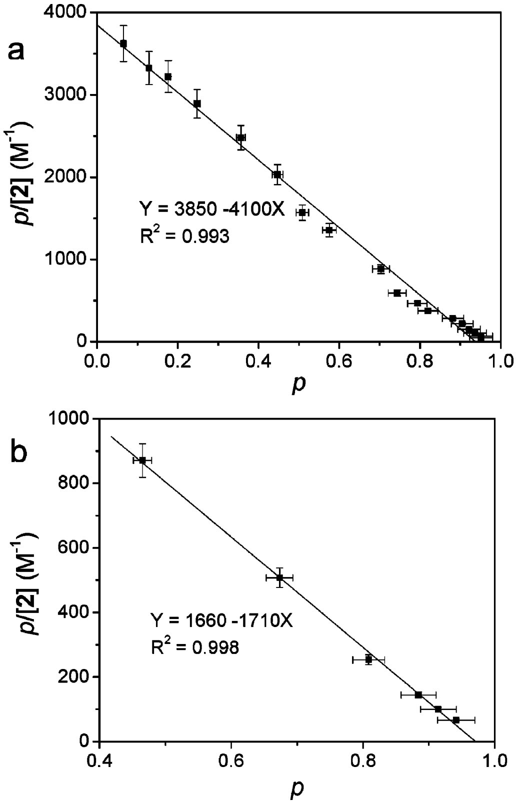


FIGURE 4. Scatchard plots for the complexation of cylindrical bis(crown ether) host **1** with paraquat **2** in 5:1 CD_3COCD_3/$CDCl_3$ (a, top) and CD_3COCD_3 (b, bottom) at 22 °C. *p* = fraction of crown ether units bound. Error bars in *p*: ±0.03 absolute; error bars in *p*/[**2**]: ±0.06 relative.

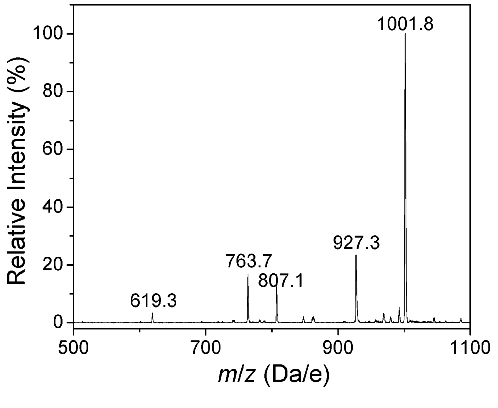


FIGURE 5. Electrospray mass spectrum of a solution of **1** and **2** (molar ratio 1:2) in a mixture of acetonitrile and chloroform (4:1).

Electrospray Ionization Mass Spectrometry. The electrospray ionization mass spectrum (Figure 5) of a solution of **1** and **2** confirmed their strong complexation. The strongest (base) peak was found at *m/z* 1001.8, due to $[\mathbf{1}\cdot\mathbf{2}_2 - 2PF_6]^{2+}$. This indicated that the 1:2 complex is very stable. A weak peak was also found for $\mathbf{1}\cdot\mathbf{2}_2$: *m/z* 619.3, $[\mathbf{1}\cdot\mathbf{2}_2 - 3PF_6]^{3+}$ (4%). Two relevant peaks were found for **1·2**: *m/z* 927.3, $[\mathbf{1}\cdot\mathbf{2} + K - H]^{2+}$ (24%) and 763.7, $[\mathbf{1}\cdot\mathbf{2} - 2PF_6]^{2+}$ (18%). The peak at *m/z* 807.1 (13%) corresponds to the "triple ion"[15] $[\mathbf{2}_2 - PF_6]^{+}$.

X-ray Analysis of the [3]Pseudorotaxane $\mathbf{1}\cdot\mathbf{2}_2$. The formation of the 1:2 complex between **1** and **2** was confirmed by X-ray analysis (Figure 6).[16] Just like the

---

[11] Tsukube, H.; Furuta, H.; Odani, A.; Takeda, Y.; Kudo, Y.; Inoue, Y.; Liu, Y.; Sakamoto, H.; Kimura, K. In *Comprehensive Supramolecular Chemistry*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Vogtle, F., Lehn, J.-M., Eds.; Elsevier: New York, 1996; Vol. 8, p 425.

[12] Based on these NMR data, Δ_0, the difference in δ values for H_1 of **1** in the uncomplexed and fully complexed species under fast exchange, was determined by extraplotation of a plot of $\Delta = \delta - \delta_u$ vs $1/[\mathbf{2}]_0$, where δ_u is the chemical shift of H_1 of **1** in the uncomplexed state; Δ_0 = 0.399 ppm. Then $p = \Delta/\Delta_0$. See the Supporting Information.

[13] Marshall, A. G. *Biophysical Chemistry*; J. Wiley and Sons: New York, 1978; pp 70−77. Freifelder, D. M. *Physical Biochemistry*; W. H. Freeman and Co.: New York, 1982; pp 659−660. Connors, K. A. *Binding Constants*; J. Wiley and Sons: New York, 1987; pp 78−86.

[14] $K_1 = [\mathbf{1}\cdot\mathbf{2}]/\{[\mathbf{1}][\mathbf{2}]\}$ and $K_2 = [\mathbf{1}\cdot\mathbf{2}_2]/\{[\mathbf{2}][\mathbf{1}\cdot\mathbf{2}]\}$. $K_{av} = (K_1 + K_2)/2$. The value of K_{av} is equal to the y-intercept and the negative of the slope of the best fit line in Figure 4. In this case for a ditopic host, with statistical complexation the macroscopic constants have the relationship $K_2 = (1/4)\ K_1$; thus, in 5:1 acetone-d_6/chloroform-*d* K_1 = 6.4 (± 0.6) × 10^3 M^{-1} and K_2 = 1.6 (± 0.2) × 10^3 M^{-1} and in acetone-d_6 K_1 = 2.7 (± 0.3) × 10^3 M^{-1} and K_2 = 6.8 (± 0.7) × 10^2 M^{-1}.

[15] For examples of triple ions, see: Rudolph, W. W.; Irmer, G.; Hefter, G. T. *Phys. Chem. Chem. Phys.* **2003**, *5*, 5253−5261. Buchner, R.; Chen, T.; Hefter, G. *J. Phys. Chem. B* **2004**, *108*, 2365−2375.

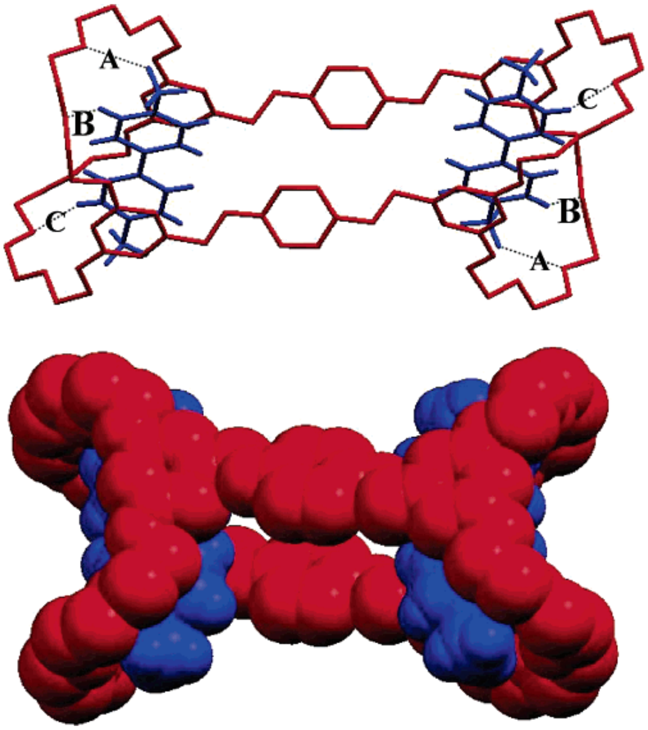


FIGURE 6. Two views of the [3]pseudorotaxane $\mathbf{1}\cdot\mathbf{2}_2\cdot(CH_3CN)_3$. **1** is red and **2** molecules are blue. Four PF_6 counterions, solvent molecules, and hydrogen atoms on **1** have been omitted for clarity. Hydrogen-bonding parameters: H···O distances (Å), C−H···O angles (deg), and C−O distances (Å): **A** = 2.56, 133, 3.31; **B** = 2.35, 142, 3.16; **C** = 2.39, 156, 3.28. Face-to-face π-stacking parameters: centroid−centroid distances (Å) and dihedral angles (deg) 4.00 and 1.3, 3.86 and 11.2.

crystal structure of the 1:1 complex between the simple crown ether host **3d** and **2**,[4c] $\mathbf{1}\cdot\mathbf{2}_2$ is stabilized by hydrogen bonding of the α-pyridinium protons (H_9) of the guest **2** with ether oxygen atoms (**B**, **C**) and face-to-face π-stacking interactions. However, there are some differences. First, *N*-methyl protons are not involved in hydrogen bonding between the host and the guest in **3d·2**, but in $\mathbf{1}\cdot\mathbf{2}_2$ one *N*-methyl proton of each guest is hydrogen bonded to an ether oxygen atom (**A**). Second, the dihedral angles/centroid−centroid distances between the two aromatic rings of the bis(*m*-phenylene)-32-crown-10 moieties are 6.9°/7.39 Å in **3d·2** and 9.4°/7.45 Å in $\mathbf{1}\cdot\mathbf{2}_2$. The conformation of **1** did not change much during the complexation as shown by Figures 1 and 6, other than the expansion of the central portion of the molecule to accommodate the guest. This demonstrated that the 3-fold improvement in association constant from **3d·2** to $\mathbf{1}\cdot\mathbf{2}_2$ is due to the preorganization inherent in **1**. The large distance, 9.58 Å, between the two closest atoms on the two paraquat guests prevents them from interacting with each other. This is consistent with the statistical nature of the complexation as discussed above.

The ^1H NMR chemical shift changes of host **1** upon complexation are consistent with a structure in solution similar to that in the solid state. Protons H_1, H_2, and H_4 of host **1** are in shielding regions of the aromatic guest **2**, while H_3 and H_5 of host **1** reside in deshielding environments provided by the guest **2**. The upfield shift of the methyl proton (H_8) of the guest **2** is consistent with its position in the shielding region of the aromatic moieties of the crown ether portions of host **1** (see Figure 6).

Conclusions

In summary, we prepared the first cylindrical host for paraquat derivatives. Its complex with paraquat has 1:2 stoichiometry. The complexation is statistical and strong. The study presented here may stimulate further studies on complexation of cylindrical hosts with other guests. Because this cylindrical bis(crown ether) host is homoditopic it can be used in future construction of supramolecular polymers and other novel architectures. Therefore, this new cylindrical bis(crown ether) host promises to be valuable in future work toward these systems.

Experimental Section

General Procedures. Dimethylformamide (DMF) was distilled under reduced pressure. Other chemicals were reagent grade and used as received. All solvents were HPLC or GC grade. Melting points were taken in capillary tubes and are uncorrected. X-ray crystal data of **1** and $\mathbf{1}\cdot\mathbf{2}_2$ were collected on a Bruker Apex CCD diffractometer equipped with Mo K_α radiation (λ = 0.71073 Å) and a graphite monochromator by the φ and ω scan method.

Synthesis of Bis[5-(*p*-hydroxyphenyoxymethyl)-1,3-phenylene]-32-crown-10 (3b). A solution of 0.400 g (0.556 mmol) of **3a**[9] in 30.0 mL of acetonitrile was added at 5 mL/h to a suspension containing 1.52 g (11.0 mmol) of potassium carbonate, 5.00 mg of tetrabutylammonium iodide, and 1.22 g (11.1 mmol) of hydroquinone in 100 mL of DMF which was heated at 110 °C. After addition, this mixture was kept at 110 °C for 24 h. The cooled mixture was rotoevaporated to remove DMF, treated with chloroform, and filtered. The organic solution was washed with deionized water (3 × 100 mL) and dried with magnesium sulfate. The solvent was removed to afford a crude product, which was purified by flash column chromatography, eluting with ethyl ether/ethyl acetate (1:1) gradually increasing to ethyl acetate to provide **3b** as a viscous liquid (0.360 g, 83%). ^1H NMR (400 MHz, $CDCl_3$, 22 °C) δ (ppm): 6.76 (8H, m), 6.54 (4H, d, J = 2.4 Hz), 6.40 (2H, t, J = 2.4 Hz), 5.16 (2H, s), 4.89 (4H, s), 4.07 (8H, t, J = 4.4 Hz), 3.84 (8H, t, J = 4.4 Hz), 3.71 (16H, m). LRFABMS (NBA) *m/z* 781 $[M + H]^+$, 706 $[M - C_6H_5O + H_3O]^+$, 672 $[M + H - C_6H_5O_2]^+$, 562 $[M - C_{12}H_{10}O_4]^+$; HRFABMS (NBA/PEG) *m/z* calcd for $[M + H]^+$ $C_{42}H_{53}O_{14}$, 781.34353, found 781.34662, error 4.0 ppm; $[M]^+$ $C_{42}H_{52}O_{14}$, 780.33571, found 780.33673, error 1.3 ppm.

Synthesis of Symmetric Cylindrical Bis(crown ether) Host (1). A solution of 144 mg (0.200 mmol) of **3a** and 156 mg (0.200 mmol) of **3b** in 30.0 mL of DMF was added via a syringe pump at 1.00 mL/h into a suspension containing 1.60 (11.5 mmol) g of potassium carbonate and 2.00 mg of tetrabutylammonium iodide in 150 mL of DMF at 110 °C. After addition, the reaction mixture was stirred at 110 °C for 5 days. The cooled mixture was evaporated to remove DMF, treated with chloroform, and filtered. Removal of chloroform afforded a crude product, which was purified by flash column chroma-

---

(16) Crystal data of $\mathbf{1}\cdot\mathbf{2}_2\cdot(C_2H_3N)_3$: needle, yellow, 0.45 × 0.05 × 0.04 mm^3, $C_{102}H_{129}O_{24}N_7P_4F_{24}$, FW 2417.00, monoclinic, space group $P2_1/c$, a = 14.0015(12) Å, b = 20.6348(18) Å, c = 20.0547(18) Å, β = 101.645(1)°; V = 5674.9(9) Å^3, Z = 2, D_c = 1.414 g cm^{-3}, T = 100 (2) K, μ = 1.78 cm^{-1}, 10 007 independent reflections (R_{int} = 0.0415), 682 parameters, R1 = 0.1101, wR2 = 0.3122 [$I > 2\sigma(I)$], and GoF = 1.092. Three disordered solvent CH_3CN molecules in the cavity of **1** were treated by the SQUEEZE program;[17] the correction of the X-ray data is 143 electron/cell, and the required value is 132 electron/cell.

(17) Spek, A. L. *J. Appl. Crystallogr.* **2003**, *36*, 7−13.

tography, eluting with ethyl acetate gradually increasing to a mixture of ethyl acetate and methanol (1:1 in volume) to afford **1** as a white solid. Yield: 80.5 mg (32%). Mp: 69.1−70.0 °C. ^{1}H NMR (400 MHz, $CDCl_3$, 22 °C) δ (ppm): 6.76 (8H, s), 6.47 (8H, d, $J = 2.4$ Hz), 6.32 (4H, t, $J = 2.4$ Hz), 4.65 (8H, s), 3.95 (16H, t, $J = 4.2$ Hz), 3.82 (16H, t, $J = 4.2$ Hz), 3.66−3.73 (32H, m). LRFABMS (NBA): *m/z* 1363 $[M + Na]^+$, 1341 $[M + H]^+$. HRFABMS (NBA/PEG): *m/z* calcd for $[M + Na]^+$ $C_{72}H_{92}O_{24}Na$ 1363.5876, found 1363.5808, error 5.0 ppm.

Complexation Studies by Proton NMR. All solutions were prepared as follows. Precisely weighed amounts of dried hosts and guests were added into separate screw cap vials. The NMR solvent was added with to-deliver volumetric pipets. Then specific volumes of each fresh solution were mixed to yield the desired concentrations. For example, to make three solutions, 0.500 mM **1**/1.00 mM **2,** 0.500 mM **1**/1.50 mM **2**, and 0.500 mM **1**/2.00 mM **2**, a 1.00 mM solution of **1** was made first by adding 7.00 mL acetone-d_6 with a 7.00 mL to-deliver pipet into a screw cap vial containing 9.39 mg (0.00700 mmol) of **1**. Then 0.300 mL of this solution was added with a 0.300 mL to-deliver pipet to three vials that contained 0.300 mL of 2.00 mM, 0.300 mL of 3.00 mM, and 0.300 mL of 4.00 mM of **2** separately. ^{1}H NMR data were collected on a temperature controlled spectrometer. Acetone-d_6 and 5:1 acetone-d_6/chloroform-*d* were chosen as the NMR solvents because all compounds used here have relatively good solubilities in them. Error bars were calculated based on a 0.05 mg deviation in weight, a 0.001 ppm deviation in chemical shift on proton NMR spectra, and a ±2% deviation in fractional complexation (Δ/Δ_0). Standard errors in both the intercept and slope coefficients based on regression were used to determine errors in association constants.

Acknowledgment. This work was supported by the National Science Foundation (DMR0097126) and the American Chemical Society Petroleum Reasearch Fund (40223-AC7).

Supporting Information Available: Proton NMR spectra of **3b** and **1**, ORTEP diagrams of the X-ray crystal structures of **1** and **1·2**$_2$, details for determination of Δ_0 of H_1 for complexation between **1** and **2** in 5:1 acetone-d_6/chloroform-*d* and acetone-d_6, and X-ray crystallographic file (CIF) for **1** and **1·2**$_2$. This material is available free of charge via the Internet at http://pubs.acs.org.

JO048111U