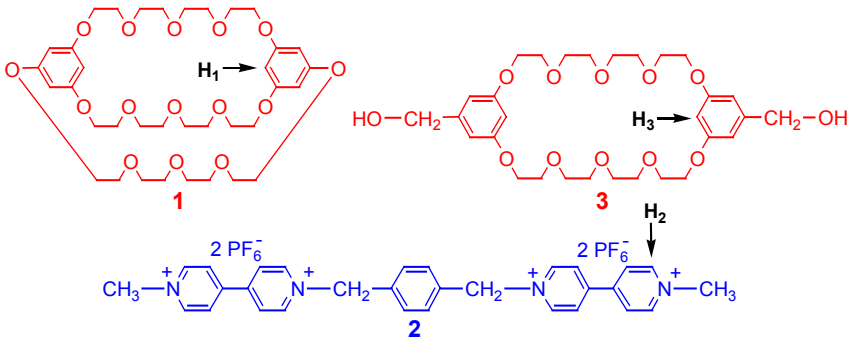
Chapter 8

First Cryptand-based [3]Pseudorotaxane: Cooperative Complexation between a Cryptand and a Bisparaquat Guest

8.1. INTRODUCUTION

Paraquat (N,N'-dialkyl-4,4'-bipyridinium) derivatives are common guests in supramolecular chemistry.[1] Bisparaquat derivatives have been widely used in the construction of pseudorotaxanes, catenanes, and rotaxanes with potential applications in electronics.[2] Cooperative complexation is the basis of enzyme control and many other vital biological processes.[3] We first demonstrated that cryptands are much better hosts than corresponding simple crown ethers for paraquat derivatives.[4] Here we report the self-assembly of the first cryptand-based [3]pseudorotaxane by cooperative complexation with a bisparaquat guest.

8.2. RESULTS AND DISCUSSION



An equimolar solution of cryptand **1**[4a] and ditopic guest **2**[5] is orange and an equimolar solution of crown ether **3**[6] and **2** is yellow due to charge transfer between the electron-rich aromatic rings of the hosts and the electron-poor pyridinium rings of guest **2**. A Job plot[7] (Figure 1) using proton NMR data of H_1 on cryptand **1** demonstrated that its complex with **2** was of 2:1 stoichiometry in acetone. The stoichiometry of the complex between crown ether **3** and **2** was determined by the mole ratio method[8] by using proton NMR data of H_2 on **2** (Figure 2) as well as a Job plot by using proton NMR data of H_3 on **3** to be 1:1 in acetone solution.

Electrospray ionization mass spectra (ESIMS) confirmed the stoichiometries of the complexes. Two relevant peaks were found for $\mathbf{1}_2$•**2**: m/z 1095 $[\mathbf{1}_2\bullet\mathbf{2} - 2PF_6]^{2+}$ and 681 $[\mathbf{1}_2\bullet\mathbf{2} - 3PF_6]^{3+}$. The ESIMS of a solution of crown ether **3** and guest **2** revealed only a 1:1 stoichiometry. Two relevant peaks were found: m/z 675 $[\mathbf{3}\bullet\mathbf{2} - 2PF_6 + H_2O]^{2+}$ and 396 $[\mathbf{3}\bullet\mathbf{2} - 3PF_6]^{3+}$.

Further proof of the formation of the first cryptand-based [3]pseudorotaxane $\mathbf{1}_2$•**2** is obtained from its X-ray structure (Figure 3).[9] Just like the crystal structures of the 1:1 and 2:1 complexes between cryptand 1 and paraquat,[4] $\mathbf{1}_2$•**2** is also stabilized by hydrogen-bonding and face-to-face π-stacking interactions. As in the crystal structure of the 1:1 complex between **1** and paraquat[4a] two β-protons of each paraquat unit are connected to a cryptand host by a water bridge. One α-proton of the each paraquat unit of the guest is directly hydrogen bonded to the host's ether oxygen. However, there are some differences. In the complex between 1 and paraquat, methyl hydrogens are not involved in hydrogen bonding, but in $\mathbf{1}_2$•**2**, four hydrogen bonds involve methyl protons with H···O distances of 2.54 Å and 2.57 Å and C-H···O angles of 137º and 135º and another two hydrogen bonds involve xylyl methylene protons with H···O distance of 2.24 Å and C-H···O angle of 158º. Furthermore, two hydrogen bonds involve xylyl aromatic hydrogens on the bridge of the bisparaquat guest with H···O distance of 2.35 Å and C-H···O angle of 150º; typical of this type of interaction;[10] this kind of aromatic H-bonding[11] effectively links the two cryptand molecules via the guest.

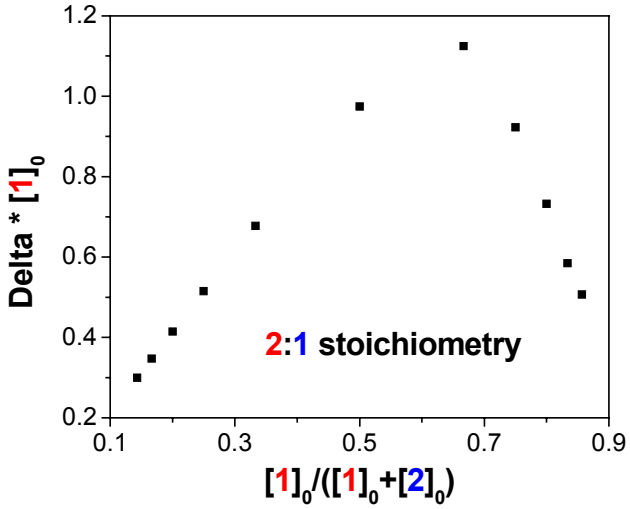


Figure 1. Job plot: the stoichiometry of the complex between cryptand **1** and ditopic guest **2** in CD_3COCD_3 solution using data for H_1. Delta is the chemical shift change corresponding to H_1. $[\mathbf{1}]_0 + [\mathbf{2}]_0 = 3.00$ mM.

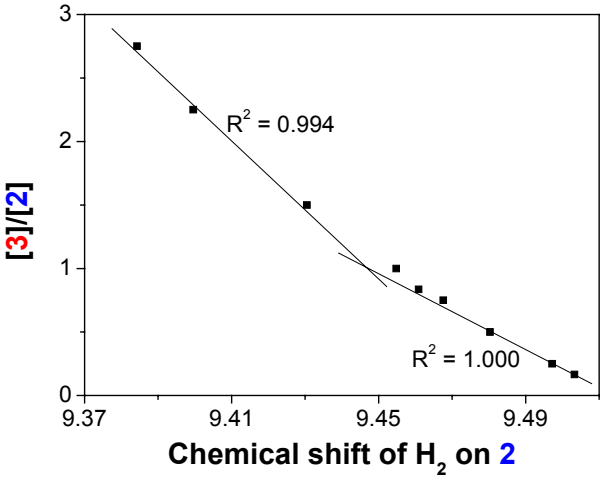


Figure 2. Mole ratio plot for **2** and **3**. The solvent is acetone-d_6.

The complexation between **2** and crown ether **3** was studied at 22 °C in acetone-d_6 by ^{1}H NMR spectroscopy. The initial concentration of guest **2** was kept constant at 0.5 mM, while the initial crown concentration was systematically varied. The extent of complexation, *p*, of the paraquat units was determined based on data for H_2 on **2**.[12] The results are shown in the form of a Scatchard plot (Figure 4a).[3,14] From the slope and the intercept we calculated the average apparent association constant 6.3 (± 0.4) × 10^2 M^{-1}, which is very close to the value, 6.6 (± 0.4) × 10^2 M^{-1}, calculated using the Benesi-Hildebrand method.[13,15]

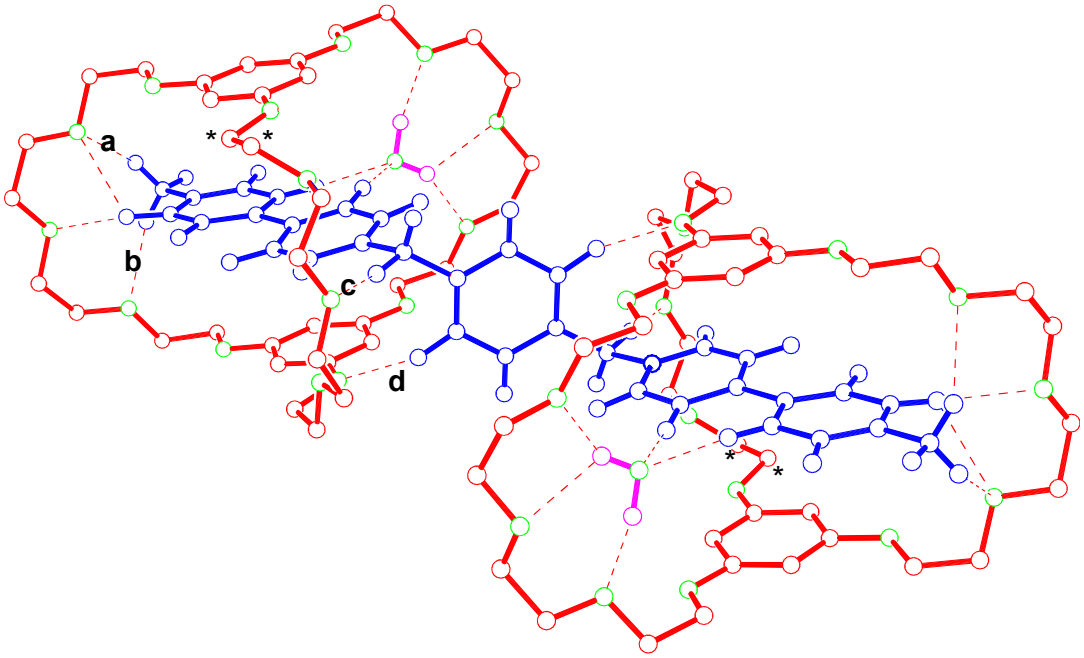


Figure 3. X-ray structure of $\mathbf{1}_2$•**2**. Oxygens are green, **2** is blue, **1** molecules are red, and water molecules are magenta. Disordered solvent molecules, four PF_6^- ions and hydrogens except the ones on **2** and water molecules have been omitted for clarity. Selected hydrogen-bond parameters: C-O distances (Å) a = 3.34, b = 3.35, c = 3.22, d = 3.36; H···O distances (Å) a = 2.54, b = 2.57, c = 2.24, d = 2.35; C-H···O angles (deg) a = 137, b = 135, c = 158, d = 150. * These four carbons are disordered.

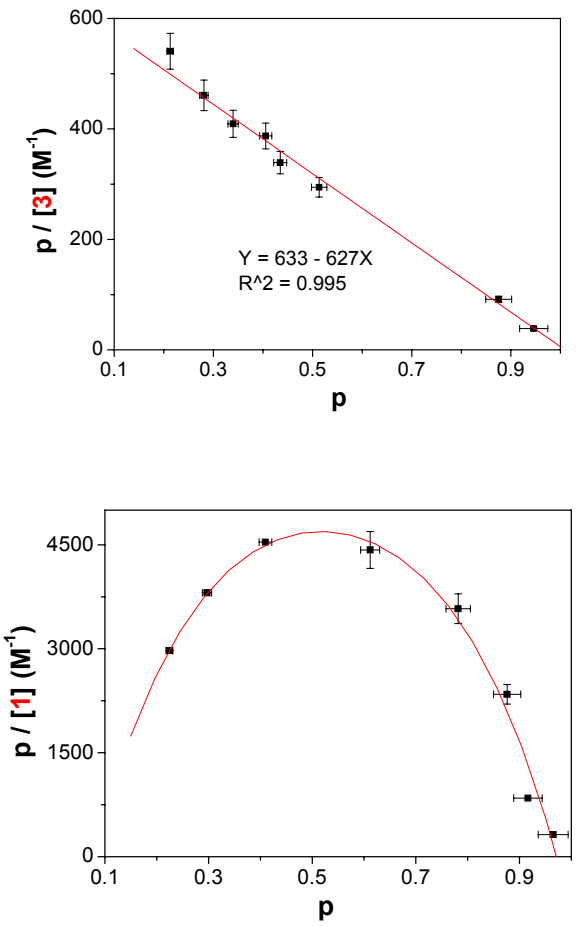


Figure 4. Scatchard plots for complexation of bisparaquat guest **2** with (a) (top) crown ether **3** and (b) (bottom) cryptand **1** in CD_3COCD_3 at 22 °C. *p* = fraction of paraquat units bound. Error bars in *p*: ± 0.03 absolute; error bars in *p*/[host]: ± 0.06 relative. The forth order polynomial fit line in b is simply to guide the eye.

In the same way a Scatchard plot (Figure 4b) for the complexation between bisparaquat **2** and cryptand **1** was obtained. The Scatchard plot is obviously nonlinear and has a maximum. This indicates that the two paraquat units of **2** act cooperatively during the complexation.[14] We hypothesize that formation of the 1:1 complex effectively restricts rotation about the N-CH_2-C_6H_4 bonds because of the hydrogen bonding of both the CH_2 and ortho protons to the cryptand (see Figure 3); this conformational restriction facilitates complexation of the second paraquat site. Another factor that may contribute is the cryptand's ability to screen the ionic cores of **2** from the nonpolar bulk solvent.

This kind of cooperative complexation was also observed between a homotritopic secondary ammonium guest and dibenzo-24-crown-8 dendrons.[16] As shown by the crystal structure of $\mathbf{1}_2$•**2** (Figure 3), the four positive charges of the guest are sealed in the cavities provided by two cryptand molecules. Therefore cooperative complexation of the bisparaquat guest was only achieved by the cryptand host. Further analysis of the Scatchard plot enables the determination of K_1 and K_2 values for $\mathbf{1}_2$•**2** system.[3] We found K_1 = 1.2 (± 0.3) × 10^3 M^{-1} and K_2 = 2.0 (± 0.5) × 10^4 M^{-1}, respectively.[17] K_2 / K_1 = 17, which is obviously higher than the value, 0.25, of K_2 / K_1 for statistical complexation**.**

8.3. CONCLUSIONS

In summary, for the first time, a cryptand was used in the preparation of a [3]pseudorotaxane and we demonstrated that cooperative complexation of a bisparaquat guest can be achieved with the cryptand host. Our current efforts are focusing on preparation of rotaxanes and catenanes based on cryptands and bisparaquat derivatives.

8.4. ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation (DMR0097126, HWG).

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9. Crystal data: prism, orange, 0.08×0.10×0.35 mm, $C_{114}H_{140}O_{38}N_4P_4F_{24}$, *FW* 2754.22, Triclinic, space group *P*-1, a = 10.974(3)**,** b = 17.451(4), c = 19.735(6) Å; α = 80.08(1)º, β = 75.44(1)º, γ = 73.94(2)º; V = 3493.8(17) Å^3, Z = 1, D_c = 1.309 g cm^{-3}, T = 100 K, μ = 1.60 cm^{-1}, 24134 measured reflections, 12707

independent reflections, 875 parameters, $F(000) = 1432.000$, $R1 = 0.0760$, $wR2 = 0.0779$ [$I > 3\sigma(I)$], maximum residual density 0.92 e•Å^{-3}, and GooF = 1.0585. Single crystals were prepared by vapor diffusion of isopropyl ether into an acetonitrile solution of **1** and **2** (molar ratio 3:1).

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12. ^{1}H NMR characterizations were done on solutions with constant [**2**] and varied [**3**]. Based on these NMR data, Δ_0, the difference in δ values for H_2 of **2** in the uncomplexed and fully complexed species, was calculated by using the Benesi-Hildebrand method.[13] Then $p = \Delta/\Delta_0$.
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15. Apparent association constant, K_a, was calculated from $K_a = p[\mathbf{2}]_0/\{(1\text{-p})[\mathbf{2}]_0\}([\mathbf{3}]_0\text{-}p[\mathbf{2}]_0)$. Errors are based on a 6% variation in K_a values.
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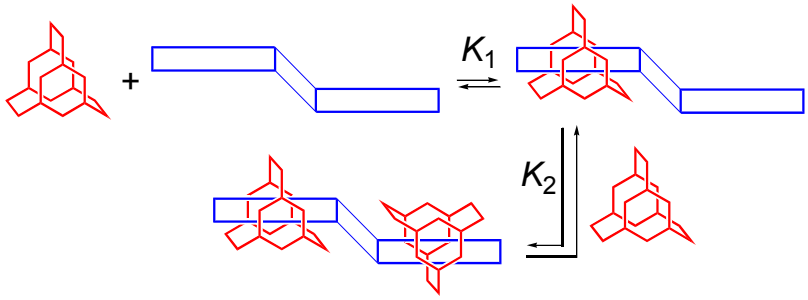
17. K_1 and K_2 are association constants corresponding to complexations of the first cryptand and second cryptand with the bisparaquat. The slope of the first three data points for low p (Figure 4b) gave the value of $2K_2 - K_1$, while the slope of the last four data points for high p (Figure 4b) gave the value of $-2K_2$.[3] Errors of the two apparent association constants were calculated based on errors of the slopes.

TOC Graphic:



Abstract: The formation of the first cryptand/bisparaquat [3]pseudorotaxane appears to be highly cooperative. The apparent value of K_2 is 17-times that of K_1.