pH-Controlled assembly and disassembly of a cryptand/paraquat [2]pseudorotaxane

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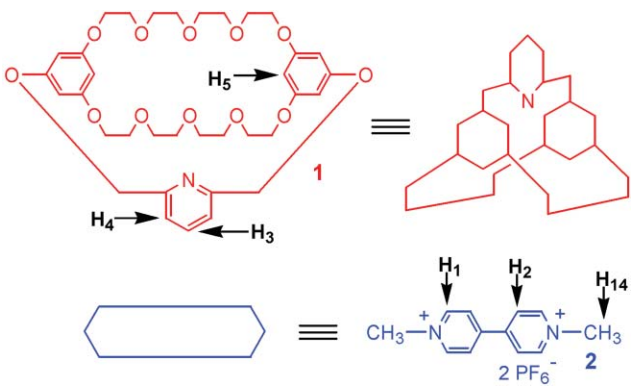
Strong complexation between a pyridine-containing cryptand and paraquat can be reversibly switched off (and back on) by adding acid (and then base).

Supramolecular complexes are attractive to scientists not only due to their topological importance, but also because of their applications in the construction of artificial molecular machines which respond to appropriate external stimuli.[1,2] Pseudorotaxanes are precursors of rotaxanes.[3] The ability to modulate the attractive/repulsive forces between cyclic and linear components of pseudorotaxanes can be readily translated to reversible control of the locus of the cyclic moiety in rotaxane analogs and thereby enable manipulation of molecular machines based on these supramolecular systems. Several methods have been employed for this purpose, including chemical, thermal, electrochemical, and/or photochemical stimuli.[1,2]

Recently we demonstrated that bis(*m*-phenylene)-32-crown-10-based cryptands are powerful hosts for paraquat derivatives.[4] Although pH control of the ability of guest species to form pseudorotaxanes and of their location in rotaxanes is well known,[1,2,5] herein we report the first acid–base responsive host, a pyridine-containing cryptand. This enables for the first time, the direct pH control of pseudorotaxanes and rotaxanes based on *N*,*N*′-dimethyl-4,4′-bipyridinium ("dimethyl paraquat" or "dimethyl viologen") and related salts.



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Previous studies have shown that the complex between cryptand host **1** and paraquat guest **2** has 1:1 stoichiometry in solution.[4d] Solutions of **1** and **2** have a bright yellow color due to charge transfer between the electron-rich aromatic rings of host **1** and the electron-poor pyridinium rings of guest **2**. In 2.00 mM **1** and **2** in acetone-d_6, the percentage of complexed **1** or **2** was calculated to be 78% based on the chemical shift change of H_5. When 5 drops of trifluoroacetic acid were added into 0.6 mL of this solution, the percentage of complexed **2** decreased to ~0%; the chemical shifts corresponding to H_1 and H_2 of paraquat **2** returned to almost their uncomplexed values (spectra c and e in Fig. 1), indicating that the complexation between cryptand host **1** and paraquat guest **2** was essentially totally quenched. After 10 drops of triethylamine were added to this solution, complexation between **1** and **2** was recovered; large changes of the chemical shifts corresponding to H_1 and H_2 were observed again (spectra d and e in Fig. 1).[6]

Similar proton NMR experiments were carried out on a solution of 2.00 mM **1** (Fig. 2). It was found that protonation of the pyridyl nitrogen atom on cryptand **1** is reversible based on changes of chemical shifts corresponding to H_3 and H_4 of cryptand **1**.[7]

These experiments demonstrate that the complexation between pyridine-containing cryptand **1** and paraquat **2** can be controlled reversibly by changing the solution pH as shown in Scheme 1. This control process is due to the reversible protonation of the pyridyl nitrogen atom of cryptand host **1**.

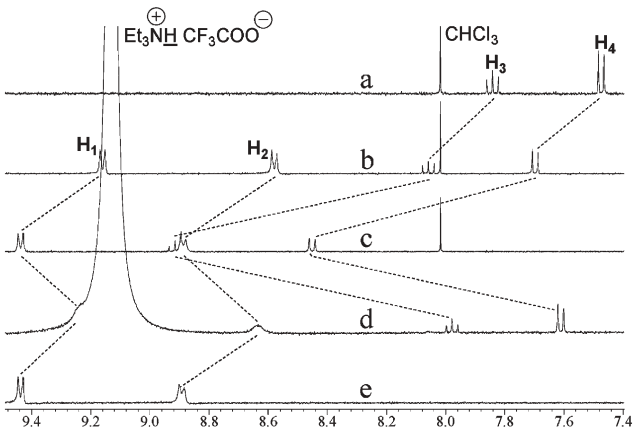


Fig. 1 Partial proton NMR spectra (400 MHz, acetone-d_6, 22 °C) of (a) 2.00 mM cryptand **1**, (b) 2.00 mM cryptand **1** and paraquat **2**, (c) a solution of 5 drops of trifluoroacetic acid and 0.6 mL of 2.00 mM cryptand **1** and paraquat **2**, (d) a solution of 5 drops of trifluoroacetic acid, 10 drops of triethylamine, and 0.6 mL of 2.00 mM cryptand **1** and paraquat **2**, and (e) 2.00 mM **2**.

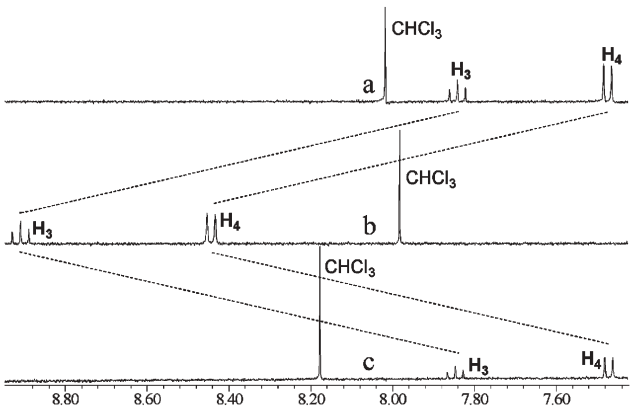
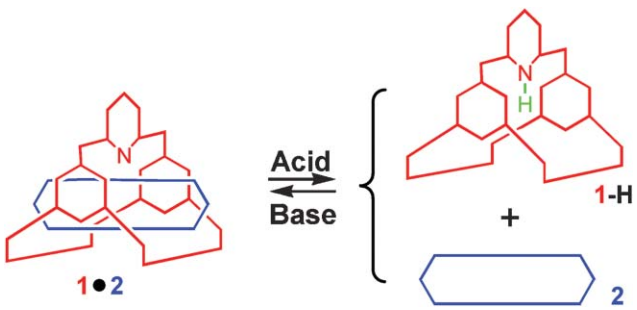


Fig. 2 Partial proton NMR spectra (400 MHz, acetone-d_6, 22 °C) of (a) 2.00 mM cryptand **1**, (b) a solution of 5 drops of trifluoroacetic acid and 0.6 mL of 2.00 mM cryptand **1**, and (c) a solution of 5 drops of trifluoroacetic acid, 10 drops of triethylamine, and 0.6 mL of 2.00 mM cryptand **1**.



Scheme 1 An acid–base controllable cryptand/paraquat [2]pseudorotaxane *via* protonation–deprotonation of host **1**.

However, the exceptionally strong (K_a = 5.0 × 10^6 M^{-1}) complexation between pyridine-containing cryptand **3**[4d] and paraquat **2** can not be controlled by changing the solution pH. No chemical shift changes were observed for any protons on cryptand **3** after trifluoroacetic acid was added (Figs. 3 and 4). This is due to the fact that the pyridyl nitrogen atom of cryptand **3** is less basic than that of host **1** due to its low electron density resulting from the electron-withdrawing ester groups attached to the pyridine ring. Therefore, this pseudorotaxane system is immune to such pH changes under these conditions.

In summary, we have demonstrated that the complexation between pyridine-containing cryptand **1** and paraquat **2** can be controlled by changing the solution pH due to the reversible protonation of the pyridyl nitrogen atom. This is important not only because this can be applied in the fabrication of rotaxane-based molecular machines, but also because the manipulation of previously reported rotaxane systems was based on changes on the guest species in response to pH,[5] whereas here the modulation of the cryptand/paraquat [2]pseudorotaxane relies on the pH sensitivity of the host. Future work will be to apply this system in the construction of molecular machines, some in combination with the **2**·**3** system which is not responsive to pH changes.

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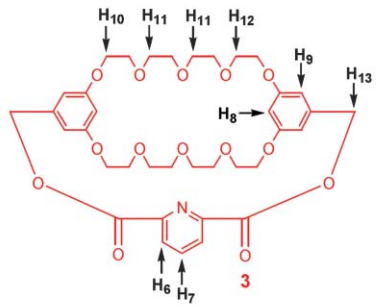

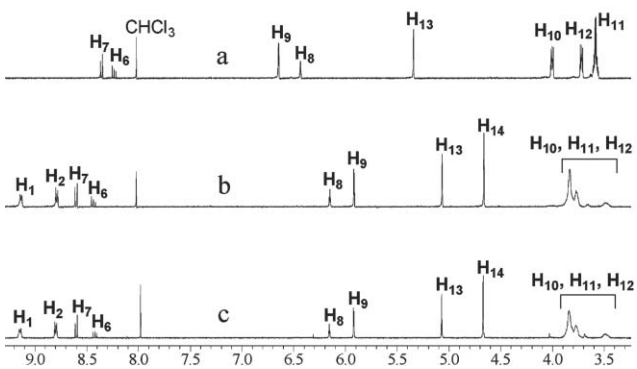

Fig. 3 Partial proton NMR spectra (400 MHz, acetone-d_6, 22 °C) of (a) 2.00 mM cryptand **3**, (b) 2.00 mM cryptand **3** and paraquat **2**, and (c) a solution of 5 drops of trifluoroacetic acid and 0.6 mL of 2.00 mM **3** and **2**.

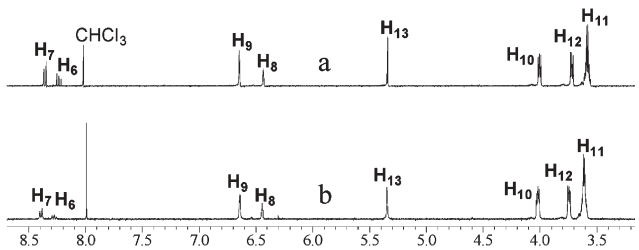

Fig. 4 Partial proton NMR spectra (400 MHz, acetone-d_6, 22 °C) of (a) 2.00 mM cryptand **3** and (b) a solution of 5 drops of trifluoroacetic acid and 0.6 mL of 2.00 mM cryptand **3**.

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6 Chemical shifts corresponding to H_1, H_2, H_4, and H_5 in the original solution of **1** and **2** were not fully recovered (spectra b and d in Fig. 1). Two possible reasons are: 1) the solution was diluted due to the additions of trifluoroacetic acid and triethylamine; 2) the ionic strength of the solution increased due to the production of $Et_3NH^+TFA^-$ salt. Both factors could change the chemical shifts and/or decrease the complexation percentage.

7 The chemical shift of the chloroform proton was affected by the pH changes (Fig. 2). This is not surprising considering that chloroform undoubtedly hydrogen bonds to cryptand **1** and trifluoroacetate anion.