

Unprecedented host-induced intramolecular charge-transfer complex formation†

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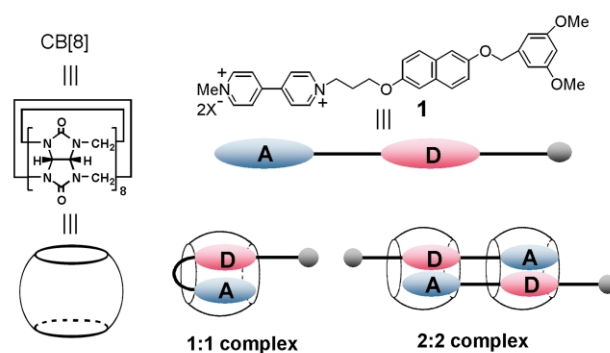
For the first time, host-induced intramolecular charge-transfer complex formation in a guest containing both an electron donor and an electron acceptor is demonstrated in the cucurbit[8]uril cavity, leading to unusual back-folding of the guest molecule.

Donor–acceptor interactions or charge transfer (CT) interactions¹ are an important class of non-covalent interactions and have been widely exploited in self-assembling systems. For example, electron deficient 4,4'-bipyridinium-based cyclophanes and derivatives have been used extensively along with electron donors to build supramolecular assemblies such as rotaxanes and catenanes,² which are important steps towards the development of artificial molecular machines.³ Although molecules containing an electron donor and an electron acceptor linked by a spacer have also been studied extensively in conjunction with the development of molecular electronic devices, synthetic metals, artificial light harvesting systems, and non-linear optical materials,⁴ only a few of them exhibit stable intramolecular CT complexation.^{5,6} Furthermore, the synergistic intramolecular CT interaction inside a host has not been reported.⁶ Here we report, for the first time, the host-induced CT complex formation between the electron-rich and electron-deficient units of a single guest molecule, resulting in the guest exhibiting unusual back-folding while residing in the host cavity.

Cucurbituril (CB[6]), a macrocycle comprising six glycoluril units, has a cavity that is accessible through two identical carbonyl laced portals.⁷ The polar carbonyl groups at the portals and the hydrophobic cavity allow the caviting to form stable host–guest complexes with small molecules.⁷ It has also been widely used as a building block for supramolecular assemblies in recent years.^{8,9} Our recent synthesis¹⁰ of larger cucurbituril homologues, cucurbit[*n*]uril (CB[*n*], *n* = 7 and 8) containing seven and eight glycoluril units, respectively, has opened up new opportunities in supramolecular chemistry.¹¹ In particular, cucurbit[8]uril (CB[8]), which has a cavity comparable to that of γ -cyclodextrin, can accommodate two different aromatic guest molecules to form a 1:1:1 host–guest complex. The formation of stable ternary complexes driven by CT interaction between electron-rich and electron-deficient guests inside the hydrophobic cavity of CB[8]¹² prompted us to study host–guest chemistry between CB[8] and a guest molecule containing an electron-rich unit and an electron-deficient unit connected by a flexible tether.

When 1 equiv. of CB[8] is added to the guest **1**, which contains a 2,6-dihydroxynaphthalene unit and a viologen unit connected by a three carbon chain, in D₂O, the solution turns violet ($\lambda_{\text{max}} = 566 \text{ nm}$) indicating the formation of a charge-transfer (CT) complex. ¹H NMR spectroscopy reveals the exclusive formation of a stable host–guest complex (**2**), which

can be either a 1:1 or 2:2 complex (Scheme 1). However, the ¹H NMR spectrum of **2** (Fig. 1), the peak assignment of which has been aided by 2D NMR techniques including COSY and ROESY (ESI†), is more consistent with a 1:1 host–guest complex in which the viologen unit of **1** folds back to form an intramolecular charge-transfer complex with the 2,6-dihydroxynaphthalene unit inside the cavity of CB[8] (Fig. 1). The signals for the viologen (*a, b, c, d*) and naphthalene (*e, f, g, and e', f', g'*) protons, which are now located inside CB[8], shift upfield relative to those in the free guest whereas those for the propylene (*k, o, m*) and 3,5-dimethoxybenzyl (*h, i, j, n*) protons, which are located outside CB[8], shift downfield. In addition to these observations, several signals (protons *a, c, j, o*) in the complex are split into two sets, which results from the magnetically non-equivalent environments due to the significant conformational restriction inside CB[8]. It should be also noted that the signal for the terminal methyl group of the viologen unit in **2** shifts upfield, which may be attributed to the shielding effect of the 3,5-dimethoxybenzene ring now located right above the methyl group due to the folded conformation.



Scheme 1 Possible host–guest complexes from cucurbit[8]uril (CB[8]) and guest **1**.

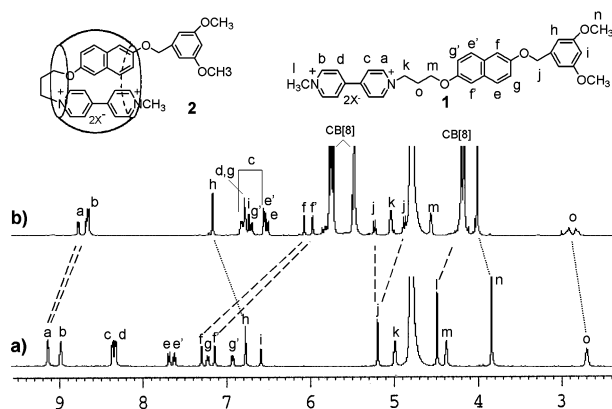


Fig. 1 Comparison of ¹H NMR spectra in D₂O of (a) guest **1** and (b) 1:1 complex **2**.

† Electronic supplementary information (ESI) available: synthetic procedure and characterization data of **1** and **2**. See <http://www.rsc.org/suppdata/cc/b2/b208280b/>

Another evidence for the formation of a 1:1 complex rather than a 2:2 complex comes from the size of the supramolecular species estimated from the diffusion coefficient measured by pulsed field gradient NMR techniques. The estimated size of the complex is only 1.3 times larger than that of CB[8] itself, supporting the 1:1 complex formation. However, the most convincing evidence for the 1:1 complex formation is provided by ESI-mass spectrometry (ESI⁺). A strong peak at 926 corresponding to the M²⁺ ion is observed with an isotopic pattern nicely matching the calculated one. Although we have been unable to obtain single crystals of **2** suitable for X-ray work, the energy-minimized structure of **2** (Fig. 2) obtained by molecular modeling (Cerius²) is congruent with the proposed structure.

To gain further insight into the nature of the intramolecular CT complex, we investigated the interaction of **2** with competing electron donor and acceptor molecules. When 2,6-dihydroxynaphthalene or *N,N'*-dimethyl-4,4'-bipyridinium dichloride is added to **2** in D₂O, no change in color or in ¹H NMR spectrum is observed. However, addition of *N,N'*-dimethyldipyridyliumethylene diiodide (MPEI), which is a stronger electron acceptor than a dialkyl-4,4'-bipyridinium unit, to **2** results in a marked change in color of the solution from violet to reddish brown. UV-visible spectroscopy reveals a large blue-shift of the charge-transfer band from 566 to 502 nm with a concomitant increase in intensity (Fig. 3). The addition of 3 equiv. of MPEI results in complete conversion of **2** to ternary complex **3** by replacing the bipyridium unit with MPEI as confirmed by ¹H NMR spectroscopy (ESI⁺). Most importantly, this experiment demonstrates that the guest in the supramolecular system changes its conformation from a folded form to an extended form in response to an external chemical stimulus, which may be therefore useful in designing chemical sensors.

In summary, we have demonstrated, for the first time, the formation of an intramolecular CT complex induced by inclusion in a molecular host, which leads to unusual back-folding of the guest molecule. Furthermore, such intramolecular

CT interaction can be disrupted by addition of competing electron donors or acceptors, which results in a large conformational change. We are currently investigating the spectroscopic and electrochemical behavior of **2**, which may demonstrate similar but reversible conformational changes of the guest triggered by light or electrochemical stimuli. This unique system may then provide an insight in designing molecular machines as well as chemical sensors.

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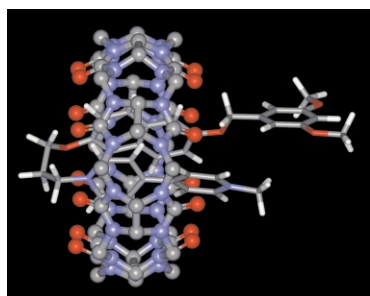


Fig. 2 Energy-minimization structure of 1:1 complex **2** obtained by Cerius² calculations. CB[8] is represented with a ball-and-stick model and the guest with a stick model. Color codes: oxygen: red; nitrogen: blue; carbon: gray; hydrogen: white. Hydrogen atoms in CB[8] are omitted for clarity.

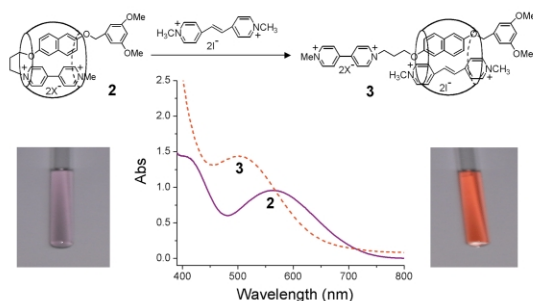


Fig. 3 Competitive host-guest interaction of 1:1 complex **2** with electron-acceptor MPEI leading to ternary complex **3**, and associated changes in the charge-transfer band: **2** (solid line) and **3** (dashed line). The UV-visible spectra were taken with 1.96 mM solutions.