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Encapsulation of Ferrocene and Peripheral Electrostatic Attachment of Viologens to Dimeric Molecular Capsules Formed by an Octaacid, Deep-Cavity Cavitand

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Abstract: In aqueous media the deep-cavity cavitand octaacid **1** forms stable dimeric molecular capsules $\mathbf{1}_2$, which are stabilized by hydrophobic effects. In this work we investigate the binding interactions in aqueous solution between these capsules and the redox active guests, ferrocene (**Fc**) and three 4,4′-bipyridinium (viologen) dications: methyl viologen ($\mathbf{MV^{2+}}$), ethyl viologen ($\mathbf{EV^{2+}}$), and butyl viologen ($\mathbf{BV^{2+}}$). Using NMR spectroscopic and electrochemical techniques we clearly show that the hydrophobic **Fc** guest is encapsulated inside $\mathbf{1}_2$. An interesting effect of this encapsulation is that the reversible voltammetric response of **Fc** is completely eliminated when it resides inside the $\mathbf{1}_2$ capsular assembly, a finding that is attributed to very slow electrochemical kinetics for the oxidation of $\mathbf{Fc@1}_2$. Diffusion coefficient measurements (PGSE NMR spectroscopy) reveal that all three viologen guests are strongly bound to the dimeric capsules. However, the ^{1}H NMR spectroscopic data are not consistent with encapsulation and the measured diffusion coefficients indicate that two viologen guests can strongly associate with a single dimeric capsule. Furthermore, the $(\mathbf{V^{2+}})_2\cdot\mathbf{1}_2$ complex is capable of encapsulating ferrocene, clearly suggesting that the viologen guests are bound externally, via coulombic interactions, to the anionic polar ends of the capsule. The electrochemical kinetic rate constants for the reduction of the viologen residue in the $\mathbf{V^{2+}}\cdot\mathbf{1}_2$ complexes were measured and found to be substantially lower than those for the free viologen guests.

Keywords: electrochemistry · ferrocene · molecular capsules · supramolecular chemistry · viologen

Introduction

Molecular encapsulation is one of the most intriguing aspects of supramolecular chemistry.[1] From Cram's carcerands and hemicarcerands[2] to the variety of molecular capsule systems developed to date,[3] many receptors can be designed and prepared to confine or trap guest molecules within their cavities. Guest confinement or encapsulation may take place in the cavity within a single molecular receptor or in a cavity formed inside a well-defined assembly of several receptors. A good deal of interest in these systems revolves around the possibility of investigating the reactivity and other properties of the encapsulated guests so that they can be compared to those observed in bulk phases.[4,5] We have previously reported on the encapsulation of redox-active organometallic compounds[6,7] inside resorcinarene molecular capsules and used ferrocenyl substituents to exert redox control on the assembly of dimeric tetraurea calix[4]-arene capsules.[8] In this work, we turn our attention to a capsular system recently reported by two of us,[9] in which a water-soluble, deep-cavity cavitand, octaacid **1**, forms dimeric molecular capsules that can include a variety of hydrophobic guests, such as steroids (Figure 1). The internal cavity of $\mathbf{1}_2$ is estimated to be about 2 nm long and 1 nm in diameter at the equator. The photochemistry of guests inside $\mathbf{1}_2$ has proven to be very different from that observed in homogeneous solution.[10–12] Here, we specifically report on the binding interactions between several electroactive guests, such as ferrocene and simple *N*,*N*′-dialkyl-4,4′-bipyridinium (viologen) derivatives (see Figure 1 for structures),

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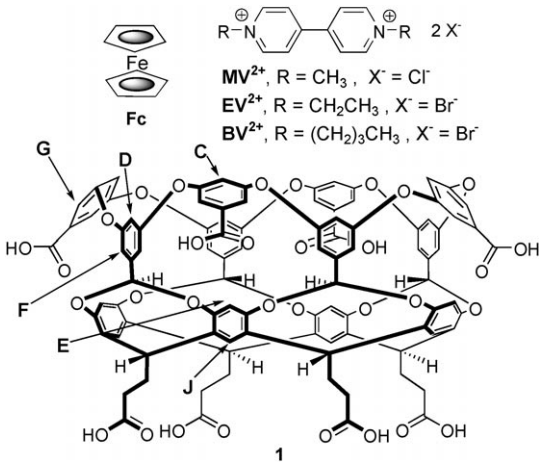


Figure 1. Structures of host **1** and the redox-active guests surveyed in this work

and host **1**. The host–guest interactions were found to be very sensitive to the hydrophobic character of the guests and provide a strong contrast between ferrocene and the viologen guests. While the former is fully encapsulated inside the dimeric capsule, the viologen guests are strongly attached to the capsule's surface via electrostatic interactions.

Results and Discussion

Encapsulation of ferrocene: The octaacid host **1** is known to form dimeric capsules that can include hydrophobic compounds in their inner cavities.[9,13,14] The formation of these capsules is basically driven by hydrophobic forces, since molecular capsule formation and guest encapsulation minimize the exposure of the guest surface and the inner surface of the host cavity to water molecules. We have investigated in detail the interactions between ferrocene (**Fc**), a hydrophobic, redox-active guest, and host **1**. The low aqueous solubility of **Fc** limits the host/guest concentration ratios that can be used in these experiments. However, Figure 2 shows the proton NMR spectra of **1** as increasing concentrations of **Fc** are added to the solution. The first experimental observation is that the presence of host **1** in the solution significantly increases the solubility of guest **Fc** over the levels that could be reached in the absence of **1**. This finding suggests the presence of binding interactions between **Fc** and **1**.

Addition of small amounts of **Fc** to the D_2O solution containing **1** leads to the appearance of a new set of peaks for the host protons. The only proton signal that is not affected by the addition of **Fc** is that at $\delta = 7.55$ ppm, which corresponds to the aromatic protons located at the bottom of the cavity (labeled "**J**" in Figure 1 and Figure 2), next to the "feet" of the cavitand host. All other proton signals are substantially affected by the guest. The **Fc**-induced signals increase, at the expense of the original host proton signals, until the added amount of **Fc** reaches about 0.5 equivalents. After this point, only the proton signals corresponding to

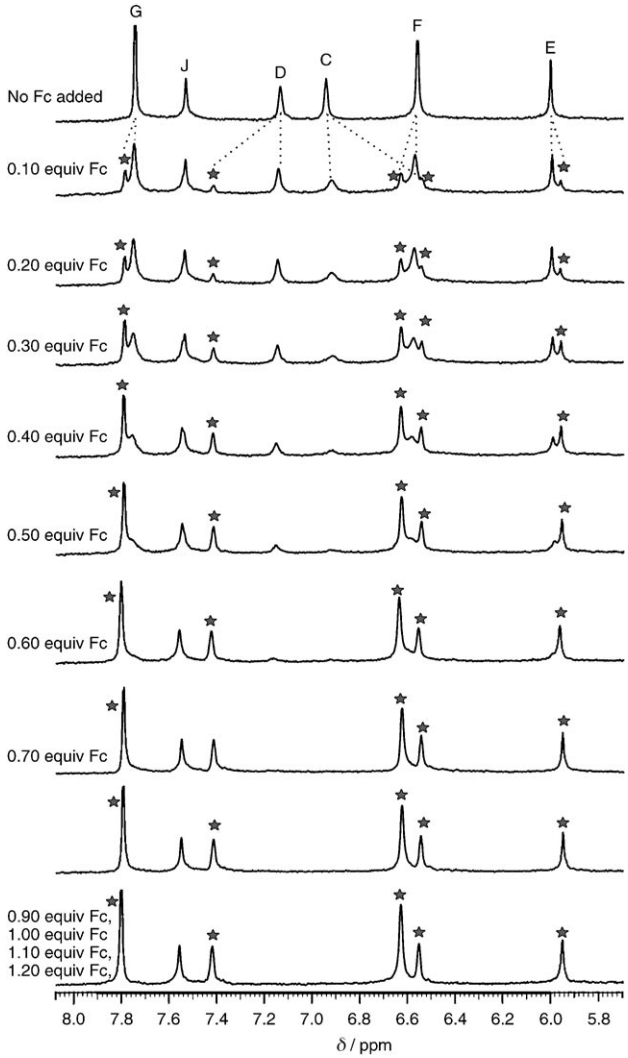


Figure 2. Partial ^{1}H NMR spectra (400 MHz, 50 mM NaCl + 10 mM borate buffer pH 8.9 in D_2O) of host **1** (1.0 mM) in the presence of increasing concentrations of **Fc**. Proton resonances labeled with a star correspond to complexed **1**.

the **Fc** complex are visible. The symmetry of the host is not broken by the inclusion of the guest and could correspond to the monomeric host (C_{4v}) or the dimeric capsule (D_{4h}). However, the fact that the protons most affected by guest inclusion are those at the cavity portal points to the head-to-head dimerization of **1** to form a capsular assembly. Furthermore, the stoichiometry of the binding interactions (2 hosts/1 guest), as revealed by the NMR spectra, suggests the encapsulation of the **Fc** guest inside the $\mathbf{1}_2$ assembly. This is also consistent with the observed chemical shift for the **Fc** protons ($\delta = 2.16$ ppm), which are considerably shifted upfield from their resonance frequency prior to encapsulation. This pronounced encapsulation-induced upfield shift is a result of the ring currents that the **Fc** protons experience while surrounded by the aromatic walls of the capsule.

The pulse gradient stimulated echo (PGSE) NMR technique has become extremely popular for the determination

of diffusion coefficients (D_o) and as a general tool to investigate molecular association phenomena in the solution phase.[15] Therefore, we measured the diffusion coefficients of the host and the guests used in this work. The D_o value of the octaacid in D_2O solution also containing 10 mM sodium tetraborate was measured as $2.2\times10^{-6}\,cm^2s^{-1}$, a value that corresponds to the monomeric form of the host. In the presence of 0.5 equivalents of **Fc**, the diffusion coefficient of the host decreases to $1.6\times10^{-6}\,cm^2s^{-1}$. The same value was obtained by using the signal corresponding to the **Fc** protons, which clearly reveals that the guest and the host diffuse at the same rate. We must point out that the error margins in the D_o measurements are consistently less than 5%, and the differences between the values assigned to dimeric and monomeric species are much larger than the standard deviations of each value. Coupled to the rest of the experimental data on this host-guest system, the diffusion coefficients provide strong support for the idea that ferrocene is encapsulated inside the capsular assembly formed by two molecules of the host.

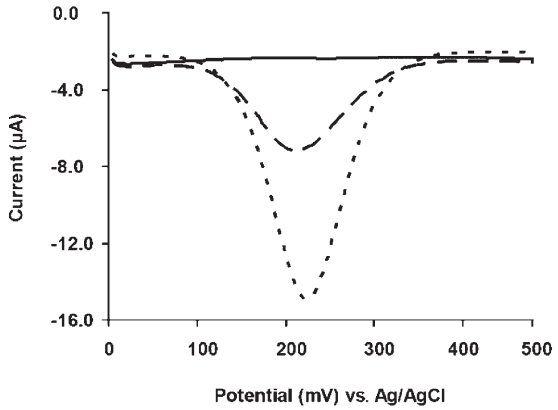


Figure 3. SWV response on a glassy carbon electrode (0.071 cm^2) of 1.0 mM host **1** in 50 mM NaCl + 10 mM pH 8.9 borate buffer in the presence of 0.5 equiv (continuous line), 1.0 equiv (discontinuous line) and 2.0 equiv (dotted line) guest **Fc**. Scan rate: 0.1 Vs^{-1}.

Ferrocene undergoes reversible (fast) one-electron oxidation to its positively charged form, ferrocenium. In the past, we have investigated the electrochemistry of ferrocene trapped inside a hemicarcerand[16] and inside hexameric molecular capsules formed by resorcinarenes.[6] We have also investigated the electrochemistry of dendrimers with a ferrocenyl core, in which dendrimer growth results in the attenuation of the corresponding electrochemical kinetics.[17,18] We were thus quite interested in recording the electrochemical behavior of **Fc** inside $\mathbf{1}_2$ molecular capsules using cyclic voltammetry (CV). The cyclic voltammograms recorded with solutions containing 0.5–1.0 mM **Fc** in the presence of two equivalents of host **1** are basically flat, with very small levels of faradaic currents that can be associated with the oxidation of ferrocene. Unfortunately these **Fc** concentration levels cannot be reached in the absence of the host, so a direct comparison of the effect of the host is not possible in aqueous solution. However, when excess amounts of **Fc** (in other words, when $[\mathbf{Fc}]>0.5\cdot[\mathbf{1}]$) are added to the solution, faradaic currents corresponding to the $\mathbf{Fc^+/Fc}$ redox couple are clearly detected and grow quickly with increasing concentrations of **Fc**. This is consistent with the excess **Fc** remaining unassociated with the molecular capsules and giving rise to larger levels of current as anticipated for freely diffusing **Fc**. Solutions with excess **Fc** become turbid, which is another indication that the excess **Fc** stays away from the capsular assembly and partially precipitates due to the low aqueous solubility of this rather hydrophobic compound.

We also recorded the electrochemical behavior of **Fc** using square-wave voltammetry (SWV), a technique more sensitive than CV. In the presence of two equivalents of host **1**, no faradaic current response was detected for **Fc** (Figure 3), in excellent agreement with the lack of faradaic current response observed in similar CV experiments. When the **Fc** concentration exceeds $0.5\cdot[\mathbf{1}]$ the faradaic response is clearly observed and the solution turns turbid immediately. Therefore, both voltammetric techniques provide the same results, regardless of their intrinsic sensitivity differences. The detection of faradaic currents in the presence of excess **Fc** (when $[\mathbf{Fc}]>0.5\cdot[\mathbf{1}]$) argues against any passivation of the electrode surface. We must conclude that **Fc** inside the dimeric molecular capsule $\mathbf{1}_2$ does not give rise to a measurable current–potential response. In agreement with similar observations in other cases in which **Fc** is encapsulated by a large organic structure,[6] we interpret this experimental fact as the result of slow heterogeneous electron transfer kinetics between the encapsulated ferrocene center and the electrode surface. Inclusion inside a sizable molecular capsule leads to an increase in the distance of maximum approach between the redox center and the electrode, which is expected to decrease the rate of electron transfer.

Interactions of simple viologen derivatives with the capsule $\mathbf{1}_2$: The binding interactions between methyl viologen ($\mathbf{MV^{2+}}$) and **1** were initially investigated by ^{1}H NMR spectroscopy in D_2O solutions also containing 10 mM sodium borate (pD = 8.9) and 40–50 mM NaCl. Addition of one or two equivalents of host **1** leads to minute changes in the chemical shifts of the aromatic protons of the viologen guest, but the resonance corresponding to the methyl protons shifts upfield by 0.15 ppm in the presence of two equivalents of **1**. Similar spectral changes were observed when other viologen guests were used instead of $\mathbf{MV^{2+}}$. In the case of butyl viologen ($\mathbf{BV^{2+}}$), the presence of two equivalents of **1** results in upfield shifts of about 0.33 ppm for the proton resonance of the terminal methyl and 0.25 ppm for the adjacent methylene on each side arm (see the Supporting Information). These spectral changes are consistent with interactions between the viologen guests and host **1**, but on their own, they do not indicate encapsulation. It is extremely important to note that the proton signals of host **1** were not affected by the addition of any of the viologen guests, in strong contrast with our experimental observations upon addition of **Fc** as a guest.

We also used PGSE NMR measurements to determine the D_o values of the viologen guests and the host. The results are given in Table 1. In the absence of **1**, all three viologens exhibit D_o values larger than $5\times10^{-6}\,cm^2s^{-1}$. However, in the presence of one to two equivalents of **1**, all the measured values are below $2\times10^{-6}\,cm^2s^{-1}$. The pronounced decrease in the diffusivity of the viologens clearly reveals a strong interaction with a much larger molecule. In fact, the D_o values measured in the presence of two equivalents **1** were identical for all viologen guests ($1.6\times10^{-6}\,cm^2s^{-1}$) and very close to the D_o value measured for the host ($1.6\times10^{-6}\,cm^2s^{-1}$) in the absence of any viologen guests. In the absence of NaCl, the diffusion coefficient of octaacid **1** is about $2.2\times10^{-6}\,cm^2s^{-1}$, which corresponds to its monomeric, unassociated form. Moderate concentrations of NaCl (< 0.1 M) tend to foster host dimerization and D_o values in the range $1.5–1.7\times10^{-6}\,cm^2s^{-1}$, and higher NaCl concentrations give rise to larger aggregates with lower diffusion coefficients. Therefore, the data in Table 1 provide evidence for the strong association of all three viologen guests with molecular capsules formed by two molecules of the octaacid host ($\mathbf{1}_2$).

Table 1. Diffusion coefficients (cm^2s^{-1}) of viologens guests measured at 25 °C in 40 mM NaCl/D_2O buffered at pD 8.9 with 10 mM sodium borate. The standard deviations of all values were found to be $<0.1\times10^{-6}\,cm^2s^{-1}$.

Guest	[Guest]/[**1**]			
	∞	1.0	0.5	0[a]
$\mathbf{MV^{2+}}$	7.6×10^{-6}	1.6×10^{-6}	1.6×10^{-6}	1.7×10^{-6}
$\mathbf{EV^{2+}}$	6.7×10^{-6}	1.5×10^{-6}	1.6×10^{-6}	1.7×10^{-6}
$\mathbf{BV^{2+}}$	5.4×10^{-6}	1.3×10^{-6}	1.6×10^{-6}	1.7×10^{-6}

[a] Values in this column correspond to the diffusion coefficient of the host in the absence of viologens guests.

Are the viologens incorporated inside the $\mathbf{1}_2$ molecular capsules? The lack of effect of any of the viologen guests on the proton NMR signals of the host affords a strong argument against encapsulation in this case. Encapsulation would also be inconsistent with the minimal effects on the aromatic proton signals of the viologens upon addition of host **1**. However, the host-induced shifts on the aliphatic protons of the viologen's *N*-substituents indicate that the ends of the guests do interact with the host. To gain a better understanding of this interaction, we measured the diffusion coefficients of $\mathbf{BV^{2+}}$ at variable concentrations while keeping constant the concentration of host **1** (Figure 4). When $[\mathbf{BV^{2+}}]<[\mathbf{1}]$ the guest's D_o values are similar to those of the capsule ($1.6\times10^{-6}\,cm^2s^{-1}$). When both concentrations are equal, the diffusion coefficient reaches a minimum value, consistent with the formation of a tight external complex between the dimeric host capsule ($\mathbf{1}_2$) and the two viologen guests. Once the guest's concentration exceeds the host concentration, the D_o values start to increase. This behavior strongly suggests that each $\mathbf{1}_2$ molecular capsule has *two external sites* for strong association of the viologen guests. Once those sites are occupied, the excess guests cannot associate with the capsule so effectively and tend to diffuse freely in the solution, leading to an overall increase of the average D_o value recorded for the viologen guest. It seems reasonable to postulate that the two external binding sites for the dicationic viologen guests are the poles of the dimeric capsules, each one containing four carboxylates. A viologen can thus latch onto this polar anionic site via coulombic attractive interactions. From our experimental data we cannot be more specific about the type of interaction between the viologen guest and the anionic end of the capsule. It is not clear whether the viologen inserts one of its positively charged ends in between the four anionic "feet" of the capsule (with the other end still exposed to the solution) or the electrostatic interaction involves both ends simultaneously. The first possibility would require rapid exchange between the two ends, since no difference is observed between them in the proton NMR spectra. It is also possible to postulate that the viologen is undergoing fast exchange among several docking conformations, as long as both ends of the guest are responsible for most of the interaction. Although the spectroscopic data support a polar location for the viologen guests, this is still the first example of an empty host that dimerizes to form a well-defined capsule. In this regard, viologen interactions with the equatorial carboxylates might also facilitate capsule formation.

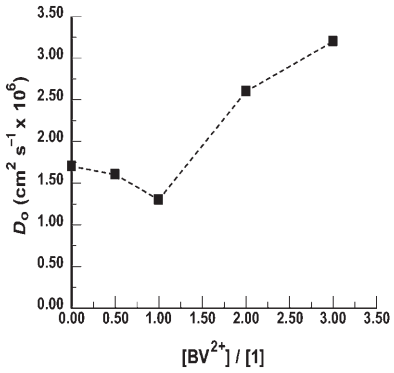


Figure 4. The diffusion coefficient of the $\mathbf{BV^{2+}}$ guest as a function of the guest/host concentration ratio. All values were measured using PGSE NMR techniques at 25 °C in 40 mM NaCl/D_2O buffered at pD 8.9 with 10 mM sodium borate and 1.0 mM host **1**. The measured D_o value for $[\mathbf{BV^{2+}}]/[\mathbf{1}]=0$ corresponds to the host and was measured using host protons.

The identification of two external binding sites for cationic guests on the structure of dimeric $\mathbf{1}_2$ capsules opens the possibility of filling the capsule up with a ferrocene guest while maintaining the interaction with the two viologen guests on the "polar caps". We have indeed verified this possibility using NMR spectroscopy. Figure 5 shows the spectrum of **1** in the presence of one equivalent of $\mathbf{EV^{2+}}$ (a $\mathbf{1}_2$ capsule interacting with two ethyl viologen guests). Addition of ferrocene results in its encapsulation inside $\mathbf{1}_2$, as evidenced by the signal at $\delta=2.16$ ppm, with no significant changes for the viologen protons. The **Fc**-induced shifts on the host protons are all consistent with its incorporation inside the capsule, leading to an *unusual self-assembled*

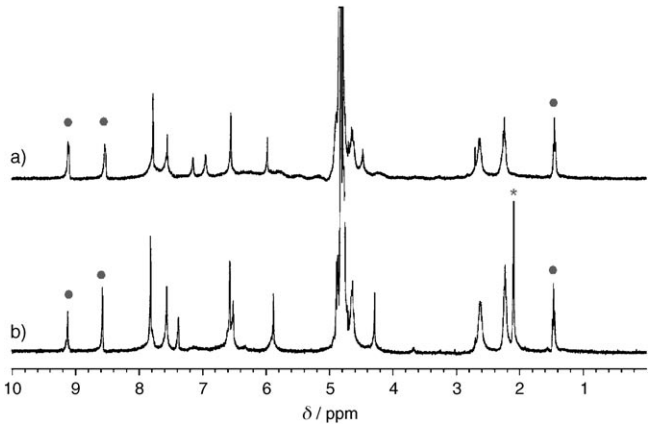


Figure 5. ^{1}H NMR spectra (400 MHz, 50 mM NaCl + 10 mM borate buffer pD = 8.9 in D_2O) of a) 2 mM $\mathbf{EV^{2+}}$ and 2 mM host **1** and b) 1 mM **Fc**, 2 mM $\mathbf{EV^{2+}}$ and 2 mM host **1**. The $\mathbf{EV^{2+}}$ protons are denoted by a circle and the encapsulated **Fc** protons by an asterisk.

structure composed of five individual components: two host molecules, an encapsulated hydrophobic guest (**Fc**) and two dicationic guests externally bound to the polar ends of the structure.

Viologens undergo two sequential, reversible, one-electron reductions. In aqueous solution, the first reduction process ($\mathbf{V^{2+}/V^{+\cdot}}$) is usually very fast, and the second reduction ($\mathbf{V^{+\cdot}/V}$), at more negative potentials, is often complicated by precipitation of the neutral, uncharged form on the electrode surface. These precipitation problems become more pronounced and extend to the cation radical form as the hydrophobic character of the viologen increases. Figure 6 shows the contrast between the cyclic voltammetric responses for $\mathbf{MV^{2+}}$ in the absence and in the presence of two equivalents of host **1**. In the absence of host, both reduction processes are clearly observed, although the anodic peak for the second redox couple is distorted due to the precipitation of the fully reduced, uncharged **MV** form. In the presence of two equivalents of **1**, both reduction processes are also observed, but the current levels for all the waves are substantially reduced, in agreement with the D_o values obtained in the PGSE NMR experiments. Notice that the presence of

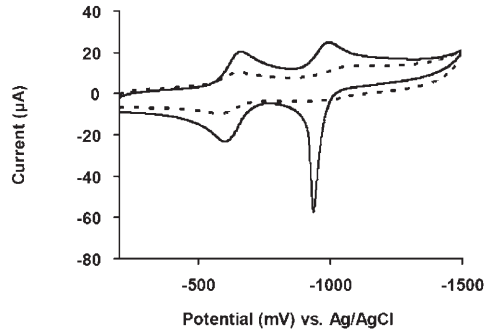


Figure 6. Cyclic voltammetric response on glassy carbon (0.071 cm^2) of 0.5 mM $\mathbf{MV^{2+}}$ in the absence (continuous line) and in the presence (discontinuous line) of 1.0 mM **1**. The aqueous solution also contains 40 mM NaCl and 10 mM sodium borate (pH 8.9). Scan rate = 0.1 $V s^{-1}$.

1 eliminates the distortion observed on the anodic peak of the second reduction process, indicating that **1** solubilizes the two-electron reduced form **MV**. The presence of **1** also increases the potential difference between the two reduction processes, suggesting the differential stabilization of the cation radical form.

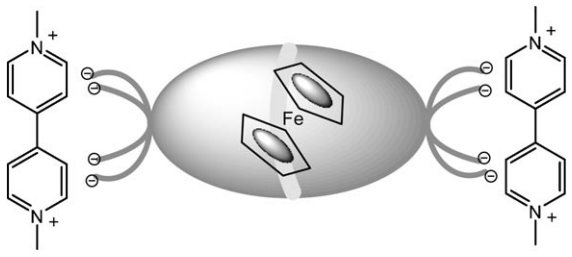
Similar voltammetric results were recorded with $\mathbf{EV^{2+}}$ and $\mathbf{BV^{2+}}$ (see the Supporting Information), although extensive precipitation effects were observed with the latter in the absence of host **1**. The voltammetric data are consistent with the strong association of every viologen guest with the dimeric $\mathbf{1}_2$ molecular capsules. The one-electron reduced form of the viologen is differentially stabilized by the capsules, which is reminiscent of similar stabilization observed in solutions containing anionic micelles.[19,20] The combined balance of electrostatic/hydrophobic forces seems to favor the interaction between the viologen cation radical and the group of four carboxylate-terminated feet on the capsule polar cap. However, the solubilization of the two-electron reduced viologen form in the aqueous medium is not so easy to explain, because any electrostatic interactions with the anionic molecular capsule are lost due to the neutral character of this viologen oxidation state. While one can argue that the reduced viologen (**MV**) may efficiently move towards the interior of the capsule, this is not consistent with the relatively fast oxidation observed for the **MV** to $\mathbf{MV^{+\cdot}}$ process in the reverse scan. It seems more reasonable to postulate that hydrophobic interactions are responsible for maintaining some degree of interaction between **MV** and the polar site.

Are the rates of heterogeneous electron transfer for the viologen compounds affected by the association with the $\mathbf{1}_2$ molecular capsule? To answer this question we recorded the scan rate dependence of the current–potential curves in the range −0.3 to −0.9 V versus Ag/AgCl, thus focusing on the first redox couple ($\mathbf{V^{2+}/V^{+\cdot}}$). These experiments were done with solutions containing 1 mM viologen guest and 2 mM host **1**, in which, according to our D_o measurements, the species present in solution is the $\mathbf{V^{2+}\cdot 1_2}$ complex. The corresponding cyclic voltammograms are shown in the Supporting Information and the standard rate constants (k^o) for heterogeneous electron transfer were determined by the Nicholson method,[21] using the diffusion coefficients obtained in the PGSE NMR experiments. We obtained k^o values of $(7.2 \pm 0.4) \times 10^{-3}$, $(3.5 \pm 0.5) \times 10^{-3}$ and $(1.7 \pm 0.2) \times 10^{-3}$ $cm s^{-1}$, for $\mathbf{MV^{2+}\cdot 1_2}$, $\mathbf{EV^{2+}\cdot 1_2}$, and $\mathbf{BV^{2+}\cdot 1_2}$, respectively. For comparison purposes we also ran the same experiments for $\mathbf{MV^{2+}}$ in the absence of host **1** and found k^o to be too fast to be determined by this method, as expected ($k^o > 0.8$ $cm s^{-1}$). Our data demonstrate that association of the viologen guest with the dimeric molecular capsule results in a pronounced decrease of the k^o value for all three viologens surveyed here. We have encountered similar attenuations of electrochemical kinetic rates in other systems in which a redox-active center is covalently or noncovalently encapsulated by a partially or fully surrounding organic sheath.[22] The strong association of the viologen guest with a large organic structure

leads to a substantially increased, average distance of maximum approach between the redox center and the electrode surface. This is equivalent to saying that the outer Helmholtz plane (OHP) moves away from the electrode surface, leading to slower electrochemical kinetics.

As part of our work with dendrimers containing a single viologen unit, we have recently shown that their electrochemical kinetics in voltammetric experiments remains reversible as the size of the dendrimer increases from first to third generation of growth.[23,24] Dendrimers containing a single viologen residue are unique in this regard, as most dendrimers of similar structure containing a single redox unit show measurably slower electrochemical kinetics (quasi-reversible to irreversible) by the second or third generation of growth.[25] We have attributed the unique behavior of viologen-containing dendrimers to orientation effects near the electrode-solution interface as the positive charge of the viologen unit is likely to be attracted by the negative charge density present on the electrode surface at the potentials required for viologen reduction.[24] This is particularly important in dendrimer structures in which the only charge resides on the viologen unit. In contrast to these viologen-containing dendrimers, the external complex formed between a viologen guest and a $\mathbf{1}_2$ dimeric capsule exhibits a total of 16 negative charges (from the two octaacid molecules) and two positive charges (from the viologen guest). Under these conditions the predominant charge on the complex is anionic and orientation effects associated with coulombic interactions between the viologen and the negatively charged electrode surface are not expected to play a significant role. Therefore, the peripheral attachment of the viologen to one of the anionic poles of the $\mathbf{1}_2$ molecular capsule has the anticipated effect of increasing the average distance of maximum approach between the viologen center and the electrode surface, leading to a measurable attenuation of the electrochemical kinetics rates.

The case reported here allows us for the first time to compare the k^o values for three similar viologens ($\mathbf{MV^{2+}}$, $\mathbf{EV^{2+}}$, and $\mathbf{BV^{2+}}$) strongly associated to the surface of the same molecular capsule system (Scheme 1). At this point we do not fully understand the reasons behind the observed gradual attenuation in the k^o value as we move from $\mathbf{MV^{2+}}\cdot\mathbf{1}_2$ to $\mathbf{EV^{2+}}\cdot\mathbf{1}_2$ to $\mathbf{BV^{2+}}\cdot\mathbf{1}_2$. The relative mass differences between these species are minimal and their D_o values are essentially identical within experimental error margins (Table 1). We note that the measured k^o values decrease in the same order as the increasing hydrophobic character of the viologen guest. However, we must continue our investigation of this system and obtain additional data before we can draw meaningful relationships between the hydrophobic character of the viologen guest and the electrochemical kinetic rates for its reduction in these assemblies.



Scheme 1. Pictorial representation of the structure of the supramolecular assembly formed by the trapped **Fc** guest, the dimeric molecular capsule $\mathbf{1}_2$ and the two externally bound viologen guests. The negative charges on the capsule's equator are not shown for simplicity.

Conclusion

The experimental results presented in this work clearly indicate that 1) ferrocene undergoes encapsulation inside dimeric $\mathbf{1}_2$ capsules, and 2) simple viologen guests bind strongly to the tetra-anionic polar ends of the capsule. Ferrocene has a pronounced hydrophobic character and undergoes encapsulation as a result of interactions with the hydrophobic cavity of the capsule, in excellent agreement with previous reports on the encapsulation of other hydrophobic compounds by $\mathbf{1}_2$.[9,13,14] $\mathbf{MV^{2+}}$, $\mathbf{EV^{2+}}$, and $\mathbf{BV^{2+}}$ are organic dications with variable degrees of hydrophobic character. Compared to **Fc**, their greater hydrophilicity and +2 charge clearly factor against encapsulation and lead to their strong interaction with the polar ends of the capsule, where favorable electrostatic forces develop between each viologen dication and the four carboxylates positioned on the capsule's end. It is interesting that the two types of binding interactions with the capsule are mutually independent, which makes possible the formation of unique supramolecular aggregates (Scheme 1) in which the hydrophobic guest (**Fc**) and one or two cationic guests ($\mathbf{V^{2+}}$) are distributed among different, albeit spatially close, locations. Among other issues, we are currently starting an investigation on the possible advantageous use of these supramolecular assemblies to carry out photo-induced electron transfer reactions.

Experimental Section

Octaacid **1** was prepared as previously reported.[9] Methyl viologen chloride and ferrocene were commercially available. Ethyl viologen and butyl viologen were prepared by exhaustive alkylation of 4,4′-bipyridine with the corresponding bromoalkane. The voltammetric experiments were recorded on a BAS 100B/W electrochemical workstation, using a single-compartment cell fitted with a glassy carbon working electrode, a Pt auxiliary electrode and a Ag/AgCl reference electrode. The working electrode was polished with 0.05 μm alumina/water slurry on a felt surface. The solutions were purged with purified nitrogen gas before the experiments and kept under an inert nitrogen atmosphere throughout. Diffusion coefficients were measured using PGSE NMR techniques as reported before.[26]

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