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Self-Assembly of 1:2 Inclusion Complexes between a Metallocycle Host and Dihydroxyaromatic Guests: A Redox Controlled Complexation Process

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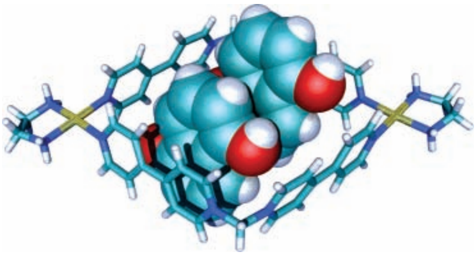
ABSTRACT



Two new 1:2 inclusion complexes were prepared by self-assembly of three components: a ligand based on 4,4′-bipyridinium, a square-planar Pd complex, and a dihydroxyaromatic guest (hydroquinone or 1,5-dihydroxynaphthalene) in a 2:2:2 ratio. Their X-ray structural analyses revealed that the complexes are stabilized by π–π stacking and [C–H···π] interactions.

The interaction of one or more substrates with a receptor is a very common issue in biological systems and an important goal of supramolecular chemistry.[1] In many cases this interaction involves the inclusion of substrates into the cavity of a host molecule. The solvent-free environments and the close proximity between guests provide a unique possibility to catalyze reactions or stabilize otherwise unstable species.[2]

Metal self-assembly has been extensively utilized for the synthesis of two- and three-dimensional supramolecular entities with well-defined internal cavities.[3] However, only a few of these superstructures can be considered as receptors for organic guests.[4] The number of hosts capable of recognizing two guest molecules resulting in the formation of 1:2 inclusion complexes is even more limited, which probably can be attributed to the difficulty in designing strong enough intermolecular interactions between the host and two guests.[5]

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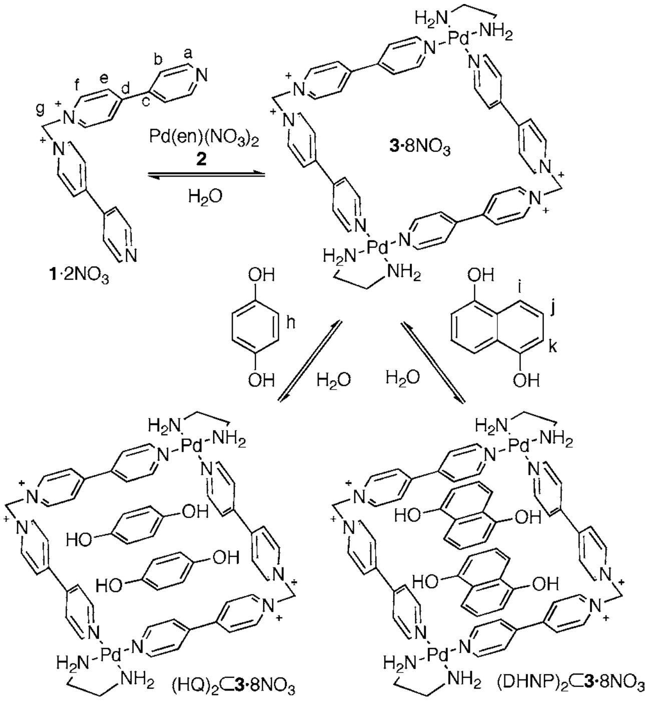
Table 1. ^1H and ^{13}C NMR Chemical Shift Data ($\Delta\delta$) for Metallocycle **3**·$8NO_3$ (5 mM) and Complexes $(HQ)_2\subset$**3**·$8NO_3$ (5 mM) and $(DHNP)_2\subset$**3**·$8NO_3$ (5 mM)[a]

compd	mol ratio					a	b	c	d	e	f	g	h	i	j	k
	1·NO_3	**2**	HQ	DHNP												
3·$8NO_3$[b]	2	2			^1H	0.21	0.10			−0.10	−0.01	0.01				
					^{13}C	2.17	2.62	2.58	−2.86	0.21	0.21	0.10				
$(HQ)_2\subset$**3**·$8NO_3$[c]	2	2	2		^1H	0.00	0.00			0.00	0.01		−0.10			
$(DHNP)_2\subset$**3**·$8NO_3$[c]	2	2		2	^1H	0.12	−0.03			−0.10	−0.01	−0.03		−2.73	−1.24	−1.01
					^{13}C	0.08	−0.13	−0.78	−0.71	−0.31	−0.30	−0.40		−2.12	−1.60	−1.56

[a] Hydrogen and carbon labels (a−k) are defined in Scheme 1. [b] The $\Delta\delta$ values are compared to those of the free ligand **1**·$2NO_3$. [c] The $\Delta\delta$ values are compared to those of the free components (metallocycle **3**·$8NO_3$ and HQ or DHNP).

As part of our continuing investigations in the field of metallocycles and catenanes based on 4,4′-bipyridinium ligands, we report the formation of inclusion complexes with 1:2 stoichiometry between a dinuclear palladium metallocycle and hydroquinone or 1,5-dihydroxynaphthalene.[6] The complexes were self-assembled in water from methylene bis-4,4′-bipyridinium ligand (**1**·$2NO_3$), the palladium complex $Pd(en)(NO_3)_2$, and the corresponding dihydroxyaromatic compound (Scheme 1).

Scheme 1. Synthesis of Inclusion Complexes



Thus, the addition of 1 equiv of palladium complex **2** to a D_2O solution of **1**·$2NO_3$ (10 mM) at room temperature gives rise to the formation of metallocycle **3**·$8NO_3$. The spectroscopic characteristics and concentration dependence of metallocycle **3**·$8NO_3$ are very similar to those of **3**·$4PF_6$·4OTf in CD_3CN.[7] Thus, the signals for Ca, Cb, and Cc in the ^{13}C NMR spectrum are shifted downfield with respect to those of the free ligand. In the ^1H NMR spectrum Ha and Hb are shifted downfield too (Table 1). DOSY (diffusion-ordered NMR spectroscopy)[8] experiments also support the proposed structure for **3**·$8NO_3$ showing very similar diffusion coefficients for **3**·$8NO_3$ and the Fujita's square (molecular square formed by 4,4′-bipyridine sides and Pd(en) corners, see the Supporting Information).[9] Moreover this coefficient is significantly smaller than its components, i.e., ligand **1**·$2NO_3$ and palladium complex **2** (see the Supporting Information). To investigate the formation of the molecular square, the self-assembly of the components was monitored by ^1H NMR at different concentrations. The spectra show how the proportion of free ligand **1**·$2NO_3$ increases as the concentration is decreased from 10 mM to 0.5 mM, the concentration at which **1**·$2NO_3$ is the major species (Figure S7, Supporting Information).

The addition of 2 equiv of hydroquinone (HQ) to a 5 mM solution of metallocycle **3**·$8NO_3$ in water produced a pale

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red coloration. This is related to the presence of an intermolecular charge transfer absorption band centered on 439 nm. However, the ^{1}H NMR spectrum does not show significant shifts with respect to that recorded in the absence of HQ, while the singlet for the aromatic protons of HQ experiences a slight upfield shift (Table 1).[10]

The crystal structure revealed the expected 1:2 inclusion compound of hydroquinone in metallocycle **3**·8NO$_3$ showing a parallel $\pi-\pi$ stacking disposition of four aromatic systems (Figure 1). The interplanar separation between internal hydroquinones (HQ$_{in}$) is 3.63 Å and the distance between the hydroquinone plane and the centroid of the closest parallel bipyridine (BIPY$_{par}$) system is 3.59 Å, so that $\pi-\pi$ interactions are maximized. The shape of the cavity is almost square, the distances between the centroids of the central C−C bonds of BIPY$_{par}$ and the orthogonal bipyridine (BIPY$_{ort}$) being 10.80 and 11.07 Å, respectively.

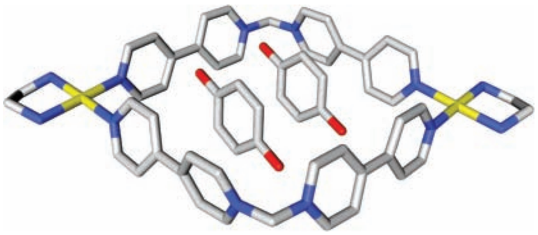

Figure 1. Crystal structure of (HQ)$_2$⊂**3**·8NO$_3$. Solvent molecules, counteranions, and hydrogen atoms have been omitted for clarity. The color labeling scheme is as follows: Pd (yellow), O (red), N (blue), and C (gray).

The HQ$_{in}$ residues present a perfectly eclipsed disposition to each other: the O−O associated vectors are tilted by 19° with respect to the mean plane of the metallocycle and each oxygen atom is involved in a bifurcated H-bond with a nitrate anion.

The $\pi-\pi$ stacking system is extended by means of $\pi-\pi$ interactions between an external hydroquinone molecule (HQ$_{ex}$) and the BIPY$_{par}$ (interplanar separation 3.49 Å) involved in the $\pi-\pi$ stacking with HQ$_{in}$ resulting in an infinite $\pi-\pi$ stacking disposition (HQ$_{ex}$/BIPY$_{par}$/HQ$_{in}$/HQ$_{in}$/BIPY$_{par}$).

It is known that 1,5-dioxonaphthalene derivatives are better π-donors and better substrates in apolar complexations than hydroquinone derivatives, so that they present a greater tendency to be located inside of bipyridinium based cavities.[11] With this in mind, it was not surprising that the addition of 2 equiv of 1,5-dihydroxynaphthalene (DHNP) to a 5 mM solution of metallocycle **3**·8NO$_3$ in water produced an intense violet coloration and an absorption band centered on 547 nm. The ^{1}H NMR spectrum, recorded on a 5 mM D$_2$O solution of **3**·8NO$_3$ in the presence of 2 equiv of DHNP, reveals a fast complexation process in the ^{1}H NMR time scale. Under these conditions the observed chemical shifts for the aromatic protons of DHNP and metallocycle are the average of the chemical shifts in the free and complexed forms weighted by its fractional populations in solution (see Table 1). The proton at the C-4 position of DHNP exhibits a significant upfield shift ($\Delta\delta = -2.7$ ppm) suggesting a [C−H···π] interaction with the orthogonal BIPY$_{ort}$ system.

Single crystals of (DHNP)$_2$⊂**3**·8NO$_3$ suitable for X-ray crystallography were obtained from a solution of DHNP/**3**·8NO$_3$ in 30 mM aqueous NaNO$_3$. The crystal structure shows the insertion of two molecules of DHNP into the cavity of the metallocycle (Figure 2). The pyridine rings of BIPY$_{par}$ are almost coplanar (torsional angle 4°), while in (HQ)$_2$⊂**3**·8NO$_3$ these pyridines are substantially twisted (29°). This can be ascribed to a stronger $\pi-\pi$ interaction with DHNP than with HQ (the distances BIPY$_{par}$/DHNP$_{in}$ and DHNP$_{in}$/DHNP$_{in}$ are 3.34 and 3.41 Å, respectively). In addition, the complex is stabilized by [C−H···π] interactions,[12] and the distance between the centroid of the pyridine ring coordinated to palladium of BIPY$_{ort}$ and the naphthalene hydrogen atom on C-4 is 3.00 Å, whereas the angle defined by these three positions amounts to 172° (Figure 2, dotted lines). The symmetry planes of DHNP guests are inclined by 70° with respect to the equatorial plane of the metallocycle. In contrast to the HQ complex, the two DHNP systems are not eclipsed but staggered with respect to one another, while their centroids are 0.75 Å below and above the mean plane of the metallocycle. The O−O associated vectors are tilted by 33° with respect to the same plane so the guests adopt an axial inclusion mode (Figure 2).

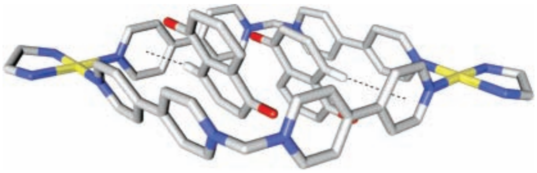

Figure 2. Crystal structure of (DHNP)$_2$⊂**3**·8NO$_3$ showing the intermolecular [C−H···π] interactions. Solvent molecules, counteranions, and hydrogen atoms have been omitted for clarity. The color labeling scheme is as follows: Pd (yellow), O (red) N (blue), C (gray), and H (light gray).

The inclusion process of HQ or DHNP can be chemically controlled by oxidation/reduction of the substrate. After addition of cerium ammonium nitrate (CAN, 1.5 equiv) to a solution of (HQ)$_2$⊂**3**·8NO$_3$ or (DHNP)$_2$⊂**3**·8NO$_3$, the substrate signals ($\delta = 6.81$ ppm for HQ and $\delta = 5.01$, 6.00, and 6.19 ppm for DHNP) disappeared, while new resonances

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[10] We have tried to determine the stoichiometry for the HQ complex in solution but no point of inflexion in the Job plot was found, indicating a low level association.

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for the corresponding quinone and the metallocycle **3**·$8NO_3$ were detected as a result of the oxidation. This process can be reversed by addition of sodium borohydride; benzoquinone was then reduced and the inclusion complex was formed again (see the Supporting Information).[13] The presence of secondary products upon the reduction with $NaBH_4$ can probably be attributed to the reduction of the pyridium moiety of the metallocycle.

To examine the electrochemical properties of the inclusion complexes, cyclic voltammetry (CV) experiments were carried out in unbuffered H_2O solutions at room temperature and compared with those of the HQ, which was identical with the recently reported one.[14] The voltammogram of $(HQ)_2{\subset}$**3**·$8NO_3$ shows that the current is decreased by 20%, which indicates that at least a fraction of HQ exists in solution as the more slowly diffusion inclusion complex (Figure 3). No significant potential shifts were observed in cathodic peaks, indicating that the oxidized species do not interact with the metallocycle.

In summary, the π-electron deficient bipyridium-based metallocycle receptor binds in water π-electron rich guests to form 1:2 inclusion complexes as a result of $\pi-\pi$ stacking, [C−H···π] interactions, and hydrophobic forces. The chemical oxidation of the guests with CAN to the corresponding quinones provokes the descomplexation, a process that can be reversed by reduction with sodium borohydride, resulting in the reformation of the inclusion complex.

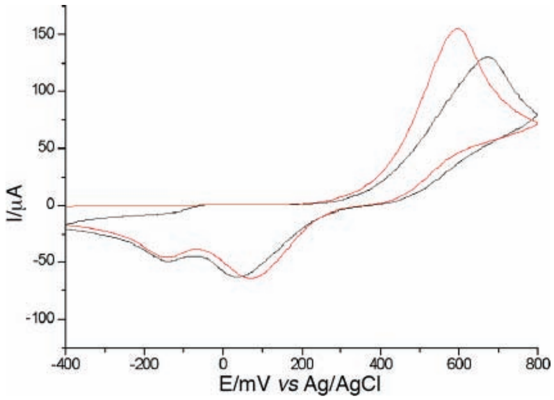

Figure 3. Cyclic voltammograms of HQ (10 mM) (red line) and $(HQ)_2{\subset}$**3**·$8NO_3$ (5 mM) (black line) in a 0.1 M aqueous solution of $NaNO_3$ at a scan rate of 100 mV/s (glassy carbon electrode vs Ag/AgCl, room temperature).

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Supporting Information Available: Synthetic procedures, NMR data, and X-ray crystallographic files (CIF) for all complexes. This material is available free of charge via the Internet at http://pubs.acs.org.

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[13] Because of the very low solubility of 1,5-naphthoquinone in D_2O the complex $(DHNP)_2{\subset}$**3**·$8NO_3$ could not be reformed upon the addition of $NaBH_4$.

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