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Inclusion of a Nitronyl Nitroxyl Radical and Its Hydrochloride in Cucurbit[8]uril

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Abstract: The recognition properties of cucurbit[8]uril (CB8) toward nitronyl nitroxide 2-(2-benzimidazolyl)-4,4,5,5-tetramethylimidazolidinyl-3-oxide-1-oxy (**1**) and its hydrochloride have been investigated. **1**·HCl led to 1:1 inclusion complex [**1**·HCl@CB8], which was characterized both in solution and by single-crystal X-ray diffraction. In this compound only the tetramethylimidazolidinyl fragment is included in the host. The magnetic behavior of the complex corresponds to a Curie law with a large separation of the spin carriers in the solid. In contrast, an insoluble species exhibiting ferromagnetic behavior is formed when pure **1** reacts with acid-free CB8. The formula [$(\mathbf{1})_2$@$(\mathrm{CB8})_3$], in which two radical guests are arranged in such a way that the phenyl groups of the benzimidazolyl substituents are both stacked into one CB8 and the tetramethyl fragments are each capped by a terminal macrocycle, is proposed, in agreement with microanalysis, spectrophotometric, EPR, and magnetic measurements. According to McConnell's rules, the alternating spin densities within the stacked aromatic fragments result in a ferromagnetic interaction ($J=+2.3\ \mathrm{cm}^{-1}$, $H=-2JS_1S_2$) and a triplet ground spin state for the inclusion complex.

Keywords: inclusion compounds · magnetic properties · nitronyl nitroxides · radicals · supramolecular chemistry

Introduction

Since the characterization of its first member, cucurbit[6]uril, in 1981,[1] the cucurbit[*n*]uril (CB*n*) family has rapidly expanded with the preparation of other homologues ($n=5$, 7, 8, 10).[2,3] Amongst systems exhibiting host properties, they are particularly attractive in being rather different from cyclodextrins and calixarenes because they have a hydrophobic cavity accessible through two identical portals composed of a rim of polar ureido carbonyl groups. These features are reflected in their host–guest chemistry, which is being extensively studied.[4] A large variety of molecular objects have been hosted in CBs; the hydrophobic cavity has potential for including various small lipophilic molecules,[5] whereas the polar rings of carbonyl groups allow association of ionized guests and particularly inorganic cations, which are associated with unprecedented binding constants.[6] Moreover, owing to their rigid structure, CBs have also found important applications as synthons for designing supramolecular assemblies: rotaxanes,[7] polyrotaxanes,[8] molecular necklaces,[9] and dendrimers[10] are examples of such applications.

One of the potential limitations of the CB family as a class of synthetic receptors is the poor solubility of most members in both aqueous and organic media. This drawback has been often overcome by using hydrochloride salts of guests because the resulting complexes are water-soluble.[4] An alternative way to perform host–guest studies with such insoluble hosts is to use appropriate organic paramagnetic guests, the behavior of which is easily detected by EPR spectroscopy in submillimolar concentrations.[11] This probe technique, which is not restricted to insoluble species, has been successfully applied to host–guest studies involving cyclodextrins,[12] calixarenes,[13] and more recently cucurbiturils.[14] The sensitivity of the paramagnetic probe to minor changes of the environment allows the inclusion process to be characterized and, in some cases, association and dissociation constants to be determined. The use of organic radical guests and EPR spectroscopy also evidenced larger supra-

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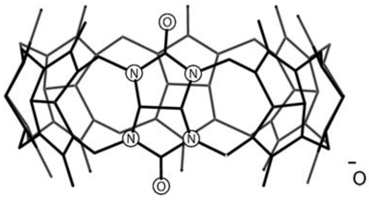
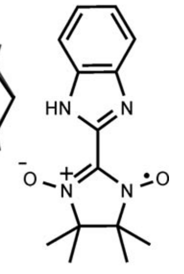
molecular species, such as fibers or triangular arrangements involving CBs.[14]

Most paramagnetic guests involved in these studies are nitroxide radicals, mainly TEMPO (2,2,6,6-tetramethylpiperidinyl-*N*-oxy) derivatives, for which well-documented synthetic organic chemistry allows guests appropriate to a host under study to be designed.[15] Among the nitroxide family, nitronyl nitroxides (NNs) also benefit from easy structural variations and, in contrast to TEMPO, they have a delocalized electronic structure.[16] This property favors intermolecular coupling pathways resulting in unprecedented magnetic properties for purely organic species, such as ferromagnetic ordering at low temperature.[17] Therefore, it was expected that with nitronyl nitroxides the role of paramagnetic guests would not be restricted to that of probing inclusion processes. They might also play the role of building blocks for designing exchange-coupled supramolecular species based on host–guest chemistry related to high-spin molecules and more generally to molecular magnetic materials. Indeed, inclusion may favor aggregation of spin carriers or, in the opposite sense, may result in an efficient screen for canceling out intermolecular magnetic interactions. Accordingly, we examined the recognition properties of CB8 towards 2-(2-benzimidazolyl)-4,4,5,5-tetramethylimidazolidinyl-3-oxide-1-oxy (**1**).[18] This radical was chosen for its high stability and because it has two groups that can each be involved in an inclusion process. In addition, the presence of a basic imidazolyl fragment opened potential for studying the inclusion properties of the derived hydrochloride. Whereas hydrochloride **1**•HCl led to a soluble 1:1 complex characterized by X-ray diffraction, **1** forms an unprecedented insoluble supramolecular species involving three CB8 hosts and two free radical guests, for which magnetic susceptibility measurements evidenced a triplet ground spin state.



$C_{48}H_{48}N_{32}O_{16}$

CB8



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Results and Discussion

On mixing **1**•HCl with CB8 or **1** with CB8•HCl in boiling water, a soluble 1:1 inclusion complex formed. Single dichroic crystals were obtained on cooling such a solution overnight. An X-ray diffraction study confirmed that these crystals are the inclusion complex [(**1**•HCl)@CB8]. The compound should be formulated as [(**1**•HCl)$_{0.88}$@CB8]•26 H_2O, that is, a solid solution of cucurbit[8]uril (12 %) and molecules of complex with **1** (88 %). In the guest, the NO distances in the 1.25–1.28 Å range are characteristic of a nitroxide radical.[19]

Because the host is located on a center of symmetry and has two identical portals, the unique included guest molecule is statistically disordered over two positions related by the center of symmetry. In the crystal, the host macrocycles form a hexagonal primitive packing that includes numerous solvate water molecules that are strongly disordered over the packing voids. The anions were not localized and are probably disordered and thus globally refined like H_2O. The C•••C distances between opposite CH groups in CB8 vary between 12.5 and 13.7 Å and the distortion parameter of CB8, Δ(CH) = 1.20 Å, well falls within the range of 0.2–2.9 Å found for all CB8 host–guest complexes.[20]

As shown in Figure 1, a large part of **1** is not included in the CB8 cavity. Only the tetramethylimidazolidine fragment is rather deeply immersed in the hydrophobic part of the host, and inclusion of the aromatic fragment is not observed. The imidazolium group of the guest is bound to a carbonyl O atom of the portal ($N{\cdots}O_{CB8}$ 2.594(7) Å). At the same time the oxyl groups are engaged into rather short contacts ($N{-}O_{oxyl}{\cdots}O_{CB8}$ 2.917(6) and 3.122(6) Å); they are both located close to the portals. As a result of these unsymmetrical interactions in the CB8 cavity, the nitroxide molecule is bent and forms an angle of 24.7° with the main axis passing through the centers of the host portals. The ONCNO and benzimidazolyl fragments are almost coplanar (within < 3°), but the imidazolidinyl ring is twisted, which extends the methyl groups in the direction perpendicular to the mean plane of the guest. Owing to this twisting and to the bent shape of the guest, lipophilic interactions between the methyl groups and the inner cavity of the host are likely optimized. This situation is similar to that described for complexes of CB8 with 4-ammonium-TEMPO and 4-methoxy-TEMPO, in which the guests are also arranged perpendicular to the equatorial plane of CB8 with the NO group and the polar group at the 4-position pointing towards the hy-

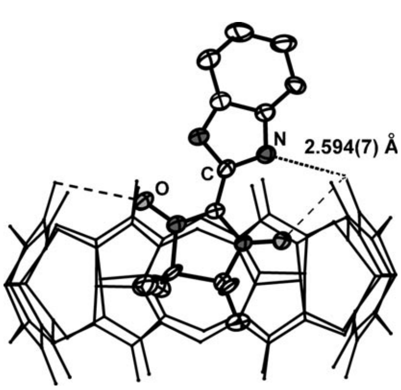

Figure 1. Side view of [**1**•HCl@CB8] showing **1** locked in the cucurbit[8]uril cavity. Thermal ellipsoids are drawn at the 50 % probability level. The hydrogen bond ($N_{Rad}{\cdots}O_{CB8}$ 2.594(7) Å) and short contacts ($O_{host}{\cdots}ON_{guest}$ 2.917(6) and 3.122(6) Å) are shown by dotted and dashed lines, respectively.

drophilic carbonyl groups and the *gem*-dimethyl groups are inserted into the hydrophobic cavity.[14b,c]

The EPR spectra of dilute preparative solutions only exhibited the characteristic five-line pattern of nitronyl nitroxides.[16] Whatever the relative concentration of the reactants, only a slight line broadening was observed and never could the presence of two species be detected. This behavior may result from fast (compared to the EPR timescale) interconversion between the free and included radical (or included and excluded complexes) or because the environment of the oxyl groups in the free and included species is not different enough. This finding is in sharp contrast with those reported in recent studies of CB8 and TEMPO derivatives, for which EPR spectroscopy allowed the free and included probes to be distinguished and the inclusion process to be studied.[14]

In contrast, spectrophotometric measurements in the $\lambda = 450–900$ nm range showed dramatic changes when CB8•HCl was added to an aqueous solution of **1** (Figure 2). The absorption pattern of **1**, centered at $\lambda = 600$ nm in H_2O,[16,21] was shifted to higher wavelengths ($\lambda = 720$ nm) with a large decrease (70%) in absorbance in the presence of CB8•HCl; in addition, the energy difference between the five peaks of the vibronic structure, which was about 1200 cm^{-1}, became larger (≈ 1450 cm^{-1}). The decrease in absorbance corresponds to protonation of the imidazole group, which results in loss of electronic communication between the ONCNO fragment and the phenyl group. However, the shift to higher wavelengths did show that the NO groups experience a less polar environment in the inclusion complex than in water. Such a shift to higher wavelengths is well documented for nitroxide radicals.[22] Note also that the larger interval defining the vibronic structure in [(**1**•HCl)@CB8] suggested that the ONCNO fragment was likely engaged in some kind of interaction with CB8 because its vibrational frequencies were modified.[23]

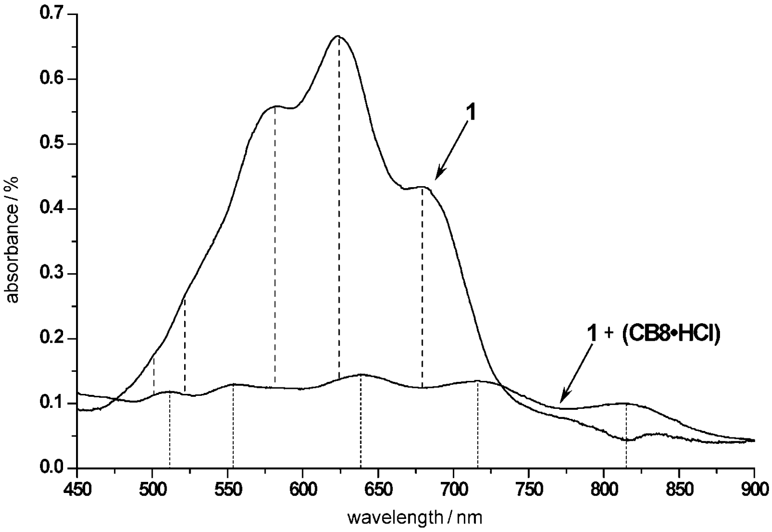

Figure 2. Vis/NIR spectra of **1** and [(**1**•HCl)@CB8] in H_2O showing the shift at high wavelength.

The dependence of the absorbance of **1** on increasing added quantities of CB8•HCl was investigated at 20 °C. The presence of an isosbestic point at $\lambda = 730$ nm established that this system is involved in a clean two-state equilibrium and, assuming a 1:1 inclusion complex, a weak association constant of $K_{\text{ass}} = 734 \pm 24\,\text{M}^{-1}$ was estimated from these data (see the Supporting Information, Figures S1 and S2). This value is lower than that reported for 4-4-methoxy-tetramethylpiperidinyl-*N*-oxy (OMe-TEMPO) with CB8 (1297 M^{-1}).[14c] A probable cause of this difference is that, in the latter case complete insertion of the radical into the host maximizes lipophilic interactions, whereas in the former only the tetramethyl fragment is inserted. The low value of the association constant, the fact that EPR spectroscopy was not able to distinguish free and included **1**, and the presence of unfilled CB8 in the crystal structure suggested that the radical is in fast exchange between the two forms in solution.

The magnetic behavior of [(**1**•HCl)@CB8] needs no comment because it was accurately modeled by a Curie law corresponding to independent spins (see the Supporting Information, Figure S3). This feature agrees well with a large separation (>10 Å) between the hosted spin carriers (see the Supporting Information, Figure S4). In the solid state, **1** is arranged into pairs with a fairly large ferromagnetic interaction (+12 K).[18] Therefore, inclusion in a macrocycle is very efficient for canceling out intermolecular interactions.

In contrast to the behavior of **1**•HCl described above, when solid acid-free CB8 was added to a hot aqueous solution of pure **1** an insoluble blue powder formed. Samples thus obtained often included nonguest macrocycle; however, addition of small portions of CB8 to a solution of **1** and extensive boiling resulted in homogeneous samples. Elemental analysis of different samples showed that both the radical and CB8 were involved in these solid compounds in slightly diverse proportions. On considering the C/N ratio, which is independent of the number of H_2O molecules involved in the compound, it was difficult to distinguish between two assemblies, [**1**@(CB8)$_2$] and [(**1**)$_2$@(CB8)$_3$].

However, by taking advantage of the fairly intense absorption of **1** in the visible range, the inclusion process was followed by UV/Vis spectrophotometry. The variation in the absorbance of **1** with increasing quantities of CB8 is shown in Figure 3. The dependence is linear and extrapolation of

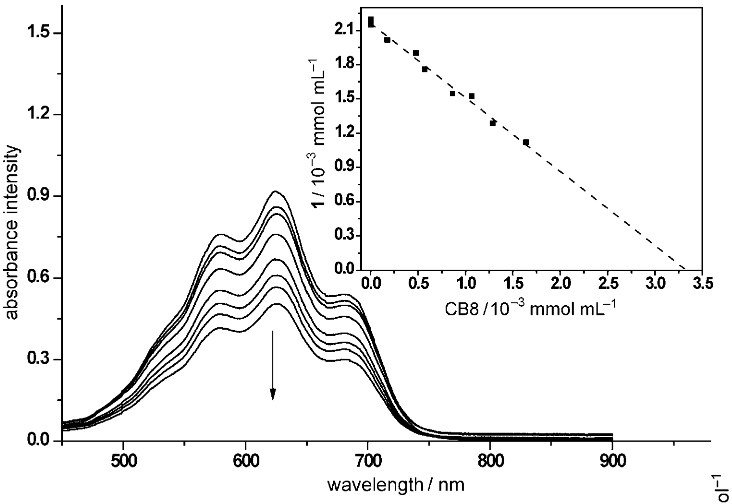

Figure 3. Decrease in absorbance of **1** on addition of increasing quantities of acid-free CB8. Inset: Dependence of the residual amount of **1** on amount of CB8; $y=-0.6348x+0.0021$, $R^2=0.988$.

the trend to total disappearance of **1** occurs for the ratio CB8/**1**=3:2 (Figure 3, inset). This simple experiment unambiguously showed that the inclusion complex should be formulated as [(**1**)$_2$@(CB8)$_3$].

The solid compounds were then investigated by using diffuse-reflectance spectrophotometry. Because the absorbance intensities of the different spectra are very diverse in magnitude, a logarithmic scale was used for better visualization (Figure 4). Compared to **1**, the most dramatic change is observed in the UV part of the spectrum of [(**1**·HCl)@CB8]. The significant decrease in absorbance intensity (about one order of magnitude) is in agreement with the presence of protonated **1**, whereas for [(**1**)$_2$@(CB8)$_3$] the intensity in the range of $\lambda=200$–380 nm is very close to that observed for **1**. In the $\lambda=450$–750 nm region, the absorption pattern for [(**1**)$_2$@(CB8)$_3$] is shifted to higher wavelengths compared to that of **1**, as is also observed for [(**1**·HCl)@CB8]. Moreover, both complexes exhibit modification of the vibronic structure. However, the absorbance behavior of [(**1**)$_2$@(CB8)$_3$] is close to that of **1**, taking into account that the relative concentration of **1** in the complex is lower. These data clearly confirm that **1** is included in CB8 in [(**1**)$_2$@(CB8)$_3$].

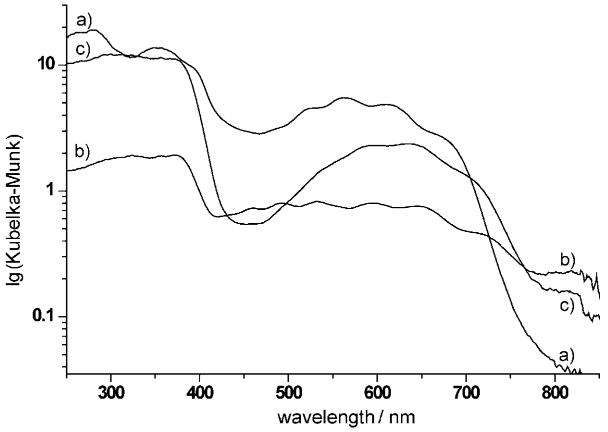

Figure 4. Diffuse reflectance spectra: a) **1**, b) [(**1**·HCl)@CB8], c) [(**1**)$_2$@(CB8)$_3$].

Further support for this formulation and information about the molecular structure came from magnetic susceptibility measurements (Figure 5). Considering [**1**@(CB8)$_2$], in which both the tetramethyl and aromatic fragments of the radical guest would be likely included each in a CB8 receptor, a Curie law would be expected because, as observed for [(**1**·HCl)@CB8]·nH$_2$O, the templating macrocycles would perfectly isolate the radicals from intermolecular interactions. In contrast, the acid-free inclusion complex exhibits ferromagnetic behavior at low temperature. Moreover, considering that the complex has the formula [(**1**)$_2$@(CB8)$_3$]·28H$_2$O according to elemental analysis (see the Experimental Section for magnetic measurements), the high-temperature (300 K) value of the product of the magnetic susceptibility with a temperature of $\chi T=0.73$ cm^3 K mol^{-1} is fairly close to the theoretical value expected for two independent spins of $^1/_2$ (0.75 cm^3 K mol^{-1}, $g=2$). On decreasing the temperature to 2 K, the value of χT remains constant down to 70 K and then increases to reach a plateau close to the value expected for a spin of 1 (1 cm^3 K mol^{-1}) at 2 K. The compound exhibits Curie–Weiss behavior with $\theta=+1.5$ K. Assuming that the molecules are well isolated, this behavior was fitted to a Bleaney–Bowers pair model to give a ferromagnetic coupling constant of $J=+2.3(4)$ cm^{-1} ($g=1.986$).[24] This study shows that nitroxide

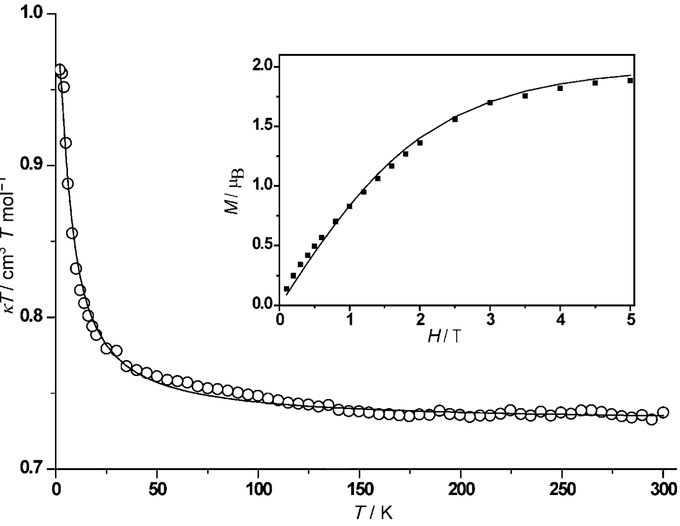

Figure 5. Magnetic behavior of [(**1**)$_2$@(CB8)$_3$] in the form of $\chi T=f(T)$. The solid line was calculated with the parameters reported in the text ($R=\Sigma(\chi_{obsd}-\chi_{calcd})^2/\Sigma(\chi_{obs}^2)=8.2\times10^{-4}$). Static magnetic field=0.5 T, sample weight=14.35 mg, diamagnetic correction $\chi_{dia}=-3.264\times10^{-3}$ cm^3 mol^{-1} (see the Experimental Section). Inset: The dependence of the magnetization on magnetic field. The solid line is the theoretical Brillouin function for $S=1$ ($R=2.3\times10^{-3}$).

radicals interact in the compound and that $[(\mathbf{1})_2@(CB8)_3]$ involving two radicals is indeed consistent with interacting radicals arranged in pairs. The same conclusion is supported by the dependence of the magnetization on the applied magnetic field at 2 K. As shown in the inset of Figure 5, this dependence is very close to the theoretical Brillouin function for $S=1$, in agreement with a triplet ground spin state.

In the solid state, EPR spectra at low temperatures displayed, in addition to the $\Delta m=1$ signal at $g=2$, a feature at $g=4$ that corresponds to the $\Delta m=2$ (see Supporting Information, Figure S5) forbidden transition expected for a triplet state.[25] The temperature dependence of the product of the doubly integrated signal intensity with temperature was in fairly good agreement with the magnetic susceptibility data in the 2–50 K temperature range.

Because a triplet ground spin state was ascertained by these experiments, the compound was confidently formulated as $[(\mathbf{1})_2@(CB8)_3]{\cdot}n\,H_2O$ that has two magnetically interacting radicals included in three CB8 receptors. Because each free radical has two fragments—tetramethylimidazolidinyl and aromatic benzimidazolyl—that may be hosted, there is only one way to arrange the five components. The two radicals should be positioned in such a way that their aromatic fragments are both stacked in one macrocycle and their tetramethyl groups are each capped by a CB8 host (Figure 6).

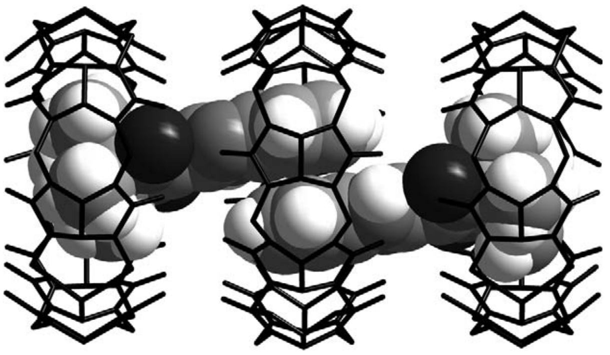

Figure 6. Molecular model of $[(\mathbf{1})_2@(CB8)_3]$ showing the inclusion of two free radicals in three CB8 hosts, generated by using HyperChem.[26]

Such a molecular arrangement in which two stacked aromatic fragments are accommodated in a CB8 receptor is not unprecedented; it has already been reported for several guests with aromatic groups.[2,27] Moreover, a synergetic effect for including two aromatic moieties into CB8 has been proposed to explain formation of 2:1 inclusion compounds independently of the stoichiometry of the reactants, as also observed for $[(\mathbf{1})_2@(CB8)_3]$.[2]

How might the two free radical guests magnetically interact in $[(\mathbf{1})_2@(CB8)_3]$? Figure 7 displays DFT calculations (see the Experimental Section) of the spin densities carried by the two radicals in the complex.[28] Most of the spin density is concentrated on the ONCNO fragments, which are too far apart to play a significant role in the coupling scheme. However, a portion of this spin density is delocalized on the aromatic fragment in an alternating pattern that is already well documented for nitronyl nitroxides substituted with an aromatic fragment at the 2-position.[29] Therefore, in the central macrocycle containing the stacked aromatic groups, each phenyl carbon atom of one radical is just in front of a phenyl carbon atom of the second guest carrying a spin density of the opposite sign. According to McConnell's rules,[30] overlap of the phenyl π orbitals should result in a ferromagnetic interaction between the two spin carriers and a ground spin state of high multiplicity, as observed herein. Similar high-multiplicity ground spin-state configurations have been observed in derivatives of *p*-cyclophanes with two spin carriers.[31] The agreement between the weakness of both the delocalized spin densities and the experimental coupling constant (+2.3 cm^{-1}) is further support for the proposed structure.

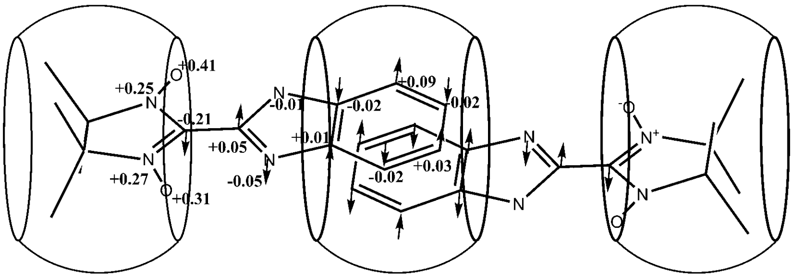

Figure 7. Schematic spin-density distribution in $[(\mathbf{1})_2@(CB8)_3]$ (see Figure S6 in the Supporting Information for a color illustration of the central part of the complex).

Conclusion

The inclusion properties of a nitronyl nitroxide guest comprised of two fragments with spin density that might be recognized by CB8, namely, 2-(2-benzimidazolyl)-4,4,5,5-tetramethylimidazolidinyl-3-oxide-1-oxy (**1**), have been investigated. Inclusion of the hydrochloride of **1** into CB8 results in a 1:1 complex, which was characterized by using single-crystal X-ray diffraction. In this complex the tetramethylimidazolidinyl fragment is deeply immersed in the cavity of the receptor as a result of interactions of the benzimidazolium fragment with carbonyl groups of the portals and lipophilic interactions involving the included *gem*-dimethyl groups. Although free **1** in the solid state is arranged in ferromagnetically coupled pairs,[18] the magnetic behavior of the [(**1**·HCl)@CB8] complex is characterized by a Curie law that corresponds to spin carriers well separated by the macrocycles.

In contrast, in [(**1**)$_2$@(CB8)$_3$] the two fragments of the nitronyl nitroxide are each included. In this supramolecular structure, two radicals are arranged head to tail; the aromatic benzimidazolyl fragments are both included and stacked in one macrocycle and the tetramethyl groups are each capped by a receptor. This disposition results in a triplet ground spin state, which was characterized by using temperature-dependent magnetic susceptibility, field-dependent magnetization, and EPR measurements.

This study illustrates potential for using synthetic receptors in the design of high-spin molecules.

Experimental Section

Elemental analyses: The elemental analyses were determined by using a EuroVector 3000 analyzer; Cl$^-$ was determined by using a standard procedure using Hg^{2+} titration.

EPR spectra: EPR spectra were recorded in dilute solution ($C \approx 5\times10^{-4}$) at ambient temperature by using a Bruker EMX spectrometer operating at X-band frequency.

UV/Vis measurements: UV/Vis spectra were performed by using a Helios Gamma Thermo Scientific spectrophotometer for solutions (20°C); diffuse-reflectance spectra of solids were recorded by using a UV-2201 Shimadzu spectrophotometer.

The ratio of CB8 to **1** in [(**1**)$_2$@(CB8)$_3$] (Figure 3) was confirmed by spectrophotometric titration as follows: variable quantities of solid CB8 (1–6 mg) were weighed directly in vials, and an aliquot of a solution of **1** (2 mL; 7.34 mg in 25 mL of H$_2$O) was added to each vial. The vials were tightly screwed shut and heated with stirring at 95°C for 30 min. After cooling to RT, the vials were centrifuged to give complete sedimentation of solid powders. The solutions were rapidly filtered directly into the optical cells ($l=1$ cm). The amount of residual radical was measured at $\lambda=681.5$ nm. The trend equation is $[\mathbf{1}]_{\text{residual}}=-0.6348\,[\text{CB8}]+0.0021$; when $[\mathbf{1}]_{\text{residual}}$ tends to zero the theoretical amount of CB8 that reacts should be 0.00331 mmol, that is, $[\text{CB8}]_{\text{final}}/[\mathbf{1}]_0=0.00331/0.00215=1.538$, which is very close to a 3:2 composition for the complex (see Inset of Figure 3).

X-ray analysis: The diffraction data were collected by using a Bruker X8 APEX CCD diffractometer (Mo$_{K\alpha}$ radiation, $\lambda=0.71073$ Å) with ω- and ϕ-scans of narrow (0.5°) frames. The structure was solved by direct methods and refined by a full-matrix least-squares technique against $|F|^2$ in anisotropic approximation using the SHELXTL program suite.[34] Hydrogen atoms were refined in geometrically calculated positions. The guest molecule has two types of disorder. Symmetrically it is disordered over two positions related by an inversion center. At the same time each position of the molecule is refined to 44% occupancy. Water molecules of solvation are strongly disordered; it is possible that some of them were not localized. $C_{60.32}H_{115.88}Cl_{0.88}N_{35.52}O_{43.78}$; crystal size $0.41\times0.41\times0.34$ mm; monoclinic; space group $P2_1/c$; $a=13.5519(7)$, $b=22.2783(12)$, $c=17.0234(7)$ Å; $\beta=93.017(2)°$; $T=92.0(2)$ K; $Z=2$; $V=5132.5(4)$ Å^3; $\rho_{\text{calcd}}=1.319\ \text{g cm}^{-3}$; $\lambda=0.71073$ Å; $2\theta_{\max}=62.74°$; $\mu=0.112\ \text{mm}^{-1}$; 36625 reflections collected within $-19\leq h\leq19$, $-32\leq k\leq23$, $-23\leq l\leq15$, 14233 unique ($R_{\text{int}}=0.0229$), $8507\,F_o\geq4\sigma(F)$, 973 parameters, $R_1=0.0983$, $wR_2=0.3435$; residual electron density peaks of 1.005 and $-0.470\ \text{e Å}^{-3}$. Absorption corrections were applied empirically ($T_{\min}/T_{\max}=0.685$).[35]

Magnetic susceptibility data: Because in these compounds the diamagnetic contributions of the constituent atoms and H$_2$O molecules of solvation were expected to be large, preliminary experiments involving CB8-(H$_2$O)$_{18}$HCl (CB8·HCl) and the diamagnetic precursor of **1** (**1**H) afforded $\chi_{\text{CB8·HCl}}=-1.12\times10^{-3}$ and $\chi_{\mathbf{1}\text{H}}=-1.58\times10^{-4}\ \text{cm}^3\text{mol}^{-1}$. Then the diamagnetic contribution of the constituent fragments of the complexes was adjusted by using literature values[36] for H$_2$O (-13×10^{-6}), H (-2×10^{-6}), and Cl (-21×10^{-6}); following this procedure gave $\chi_{\text{CB8}}=-8.68\times10^{-4}$ and $\chi_{\mathbf{1}}=-1.56\times10^{-4}\ \text{cm}^3\text{mol}^{-1}$.

For compounds [**1**@CB8]·HCl and [(**1**)$_2$@(CB8)$_3$], magnetic susceptibility data were collected in the 300–2 and 2–300 K temperature range with a applied field of 0.5 T by using a MPMS Squid magnetometer. The raw data were corrected for the sample holder and for the diamagnetic contribution of the constituent atoms, as described above. After pumping under helium in the magnetometer, the elemental analysis of [(**1**)$_2$@(CB8)$_3$] was as follows: calcd (%) for $(C_{48}H_{48}N_{32}O_{16})_3(C_{14}H_{17}N_4O_2)_2(H_2O)_{28}$: C 41.00, H 4.68, N 28.91; found: C 40.8, H 4.8, N 28.9; calculations of the magnetic susceptibilities were performed by using the corresponding molecular weight.

Molecular modeling: [(**1**)$_2$@(CB8)$_3$] was modeled by using HyperChem 7.5.[26] An initial molecule was constructed from two [1@CB8] fragments and one CB8 ring from the X-ray data. Successive optimizations utilized Amber99 molecular mechanics force-field to maintain energy restraints of the bond lengths, to ensure the rigidity of the macrocycles, and to accurately model the van der Waals radii within the CB8 cavity. During modeling with Amber99. the CB8 molecules were treated as static and all optimization energies were minimized to a root-mean-square gradient of 0.001 kJ Å^{-1}mol^{-1}.

DFT calculations: Spin densities were calculated by using the Gaussian 03 package.[32] In the first step, the geometry of the system was optimized in vacuum at the B3/LYP/3-21G(d,p) level of theory. After full optimization, a single-point calculation (B3/LYP/6-311G(d,p) level) was performed at the stationary point for determination of the spin-density values.

Preparation of inclusion complexes

[(1·HCl)@CB8]: A mixture of **1** (6 mg, 2.2×10^{-2} mmol) and CB8 ($C_{48}H_{48}N_{32}O_{16}(H_2O)_{18}HCl$) (36 mg, 2.2×10^{-2} mmol) was stirred in water (6 mL) at 95–100°C. After complete solubilization, the solution was filtered and slowly cooled overnight. The blue-green dichroic crystals that deposited (27 mg) were filtered off. The volume of mother liquor was reduced to 1 mL by slow evaporation of water over one week to give an additional crop (8 mg) of crystals (yield: 87%). Elemental analysis calcd (%) for $C_{48}H_{48}N_{32}O_{16}(C_{14}H_{14}N_4O_2Cl)_{0.88}(H_2O)_{26}$: C 35.06, H 5.47, N 24.07, Cl 1.51; found: C 35.2 , H 5.3, N 24.3, Cl 1.53.

[(1)$_2$@(CB8)$_3$]: CB8 ($C_{48}H_{48}N_{32}O_{16}(H_2O)_{18}HCl$) was purified from HCl by stirring in boiling deionized water and filtration; this procedure was repeated until the pH of the filtrate became the same as that of the water. After few days drying in air; the white powder sample corresponded to $C_{48}H_{48}N_{32}O_{16}(H_2O)_{26}$. $C_{48}H_{48}N_{32}O_{16}(H_2O)_{26}$ (25 mg) was added to **1** (3 mg) dissolved in hot H$_2$O (95°C, 5 mL) and stirred for 30 min, then the blue solid was collected by filtration, washed with H$_2$O and CH$_2$Cl$_2$, and air-dried (yield: 25 mg, 97.5%, on CB8). Elemental analysis calcd (%) for $(C_{48}H_{48}N_{32}O_{16})_3(C_{14}H_{17}N_4O_2)_2(H_2O)_{50}(CH_2Cl_2)_{1.2}$: H 5.09, C 37.33, N 26.37, Cl 1.52; found: H 5.1, C 37.2, N 26.4, Cl 1.4.

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