

Encapsulation and Stabilization of Reactive Aromatic Diazonium Ions and the Tropylium Ion Within a Supramolecular Host^[‡]

Julia L. Brumaghim,^[a] Martin Michels,^[a] Daniela Pagliero,^[a] and Kenneth N. Raymond^{*[a]}

Keywords: Supramolecular chemistry / Host–guest systems / Stabilization

Supramolecular assemblies with internal cavities are being developed as nanoscale reaction vessels to protect or modify the reactivity of guest species through encapsulation. Diazonium cations and the tropylium cation were examined for their ability to encapsulate in the tetrahedral $[\text{Ga}_4\text{L}_6]^{12-}$ supramolecular assembly. The 4-(diethylamino)benzenediazonium cation **1** readily formed a 1:1 host–guest complex with this assembly, and this encapsulation prevented **1** from re-

acting with 2,4-pentanedione in D_2O . The tropylium cation also formed a 1:1 host–guest complex with the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly, greatly slowing its decomposition in D_2O . Encapsulation in the protected environment of this host cavity alters the reactivity of these guest molecules, giving them greater stability.

(© Wiley-VCH Verlag GmbH & Co. KGaA, 69451 Weinheim, Germany, 2004)

Introduction

Chemists are beginning to develop cavity-containing supramolecular assemblies as nanoscale reaction vessels in which the reactivity of selectively encapsulated substrates can be directed by the properties of the host cavity.^[1–12] Encapsulation can also stabilize reactive intermediates or protect solvent sensitive species.^[8,13,14,15] The supramolecular $[\text{Ga}_4\text{L}_6]^{12-}$ assembly (Figure 1) has been the focus of several studies involving guest encapsulation into the tetrahedral cavity of the assembly. High affinity guests include alkyl ammonium cations,^[16] the chiral *N*-methylnicotinium cation,^[17] crown ether complexes with alkali metal cations,^[18] and cationic organometallic species that are catalysts.^[19] From these examples, it is apparent that cationic

charge, hydrophobicity, and compatible shape and size are necessary for strong encapsulation into the cavity of the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly. A remarkable feature of this cluster is its structural memory,^[20] which makes it a stable, chiral nanoscale vessel.

Results and Discussion

To expand the application of this $[\text{Ga}_4\text{L}_6]^{12-}$ assembly as a molecular reaction vessel, the reactive aromatic cations shown in Figure 2 were chosen as potential guests. The diazonium cations **1–3** were selected for their representative use in organic synthesis, and for their variation of geometry relative to the generally high-symmetry molecules known to be good guests. The tropylium cation **4** was selected for its small size and aromaticity, which would enable it to interact with the naphthyl groups on the inner faces of the cavity, and for its potential as a metal-binding ligand. Tropylium has been previously reported as a guest inside organic hosts assembled through hydrogen bonding.^[21–23]

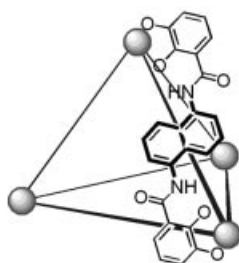


Figure 1. Schematic drawing of the $[\text{Ga}_4\text{L}_6]^{12-}$ tetrahedron showing the structure of the ligand L; lines represent additional ligand molecules, one is shown, and spheres represent gallium ions

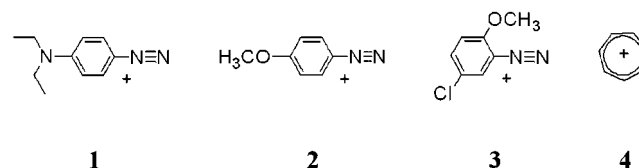


Figure 2. Structures of the test guest cations: 4-(diethylamino)benzenediazonium (**1**), 4-methoxybenzenediazonium (**2**), 5-chloro-2-methoxybenzenediazonium chloride (Diazo Red RC, **3**), tropylium ion (**4**)

[‡] Coordination Number Incommensurate Cluster Formation, 29. Part 28: Ref.^[20]

[a] Department of Chemistry, University of California, Berkeley, California 94720-1460, USA
E-mail: raymond@socrates.berkeley.edu

In order to test the ability of the assembly to encapsulate these diazonium cations, the respective tetrafluoroborate diazonium salts were dissolved in D₂O and added to the [Ga₄L₆]^{12−} assembly.^[24] When **1** was added to a solution of the assembly in D₂O, an upfield shift of the methyl triplet from $\delta = 1.20$ to -1.10 ppm was observed in the ¹H NMR spectrum (Figure 3), while the methylene resonances were seen as multiplets shifted from $\delta = 3.55$ to $\delta = 0.37$ ppm and 0.05 ppm. The large upfield shift seen for the alkyl resonances of **1** indicates its encapsulation into the tetrahedral assembly, as does the splitting of the diastereotopic methylene protons due to the chiral environment of the assembly cavity.^[25] One aromatic signal of the encapsulated guest within the [1 ⊂ Ga₄L₆]^{11−} host–guest complex can be observed as a doublet at $\delta = 3.95$ ppm shifted from $\delta = 6.85$ ppm, but the other is most likely obscured by the large HDO resonance not shown. Similar spectra were observed with CD₃OD as the solvent.

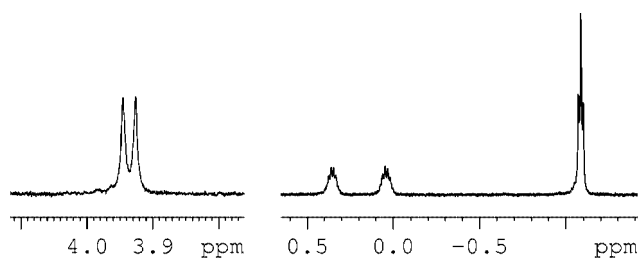


Figure 3. ¹H NMR resonances of the 4-(diethylamino)benzene-diazonium cation (**1**) encapsulated inside the [Ga₄L₆]^{12−} assembly

In initial experiments with [Ga₄L₆]^{12−} synthesized from Ga(acac)₃ (acac = acetylacetonate), addition of one equivalent of **1** resulted in the formation of a 1:1 host–guest complex, while addition of subsequent equivalents reacted with residual 2,4-pentanedione present in the NMR sample. Thus, encapsulation of the diazonium cation **1** occurs faster than the spontaneous reaction of **1** with the dione, and the sequestration of **1** in the host cavity is sufficiently rapid and strong to prevent this reaction subsequently. However, this host–guest complex is not indefinitely stable; a ¹H NMR spectrum of the solution taken after five days showed no indication of the encapsulated guest. No decomposition products of the diazonium cation were identified.

When 4-methoxybenzenediazonium (**2**) and 5-chloro-2-methoxybenzenediazonium (**3**) were added to solutions of the [Ga₄L₆]^{12−} assembly in CD₃OD, the ¹H NMR spectra revealed no shift of the diazonium cation signals in the presence of the tetrahedral host. This observation was surprising, given the ready encapsulation of **1** and the generally similar size, geometry, and charge of these three diazonium cations. The encapsulation behavior of **1** is most likely due to its greater hydrophobicity arising from the two ethyl groups on the amino nitrogen as compared with the presence of only one methyl group on the methoxy oxygen of **2** and **3**. The additional hydrophobic interactions between these four aliphatic carbon atoms and the naphthyl groups

that comprise the “walls” of the tetrahedral cavity make encapsulation of diazonium cation **1** favorable relative to **2** and **3**.

Encapsulation experiments with the tropylium cation **4** were conducted in the same manner as those for the diazonium cations. Addition of one equivalent of **4** to the [Ga₄L₆]^{12−} assembly in D₂O results in the shift of the tropylium singlet from $\delta = 6.45$ to 2.95 ppm (Figure 4, a). Integration of this upfield-shifted tropylium signal indicates that this cation is encapsulated as a guest inside the tetrahedral assembly with a 1:1 ratio. Addition of a second equivalent of tropylium ion results in a second broad resonance at $\delta = 5.18$ ppm (Figure 4, b). The upfield shift of this resonance, compared to the resonance of free tropylium in D₂O, indicates that the second equivalent of aromatic tropylium cation interacts with the [Ga₄L₆]^{12−} assembly by ion-pair association with the highly-charged assembly, as seen with other counter cations.

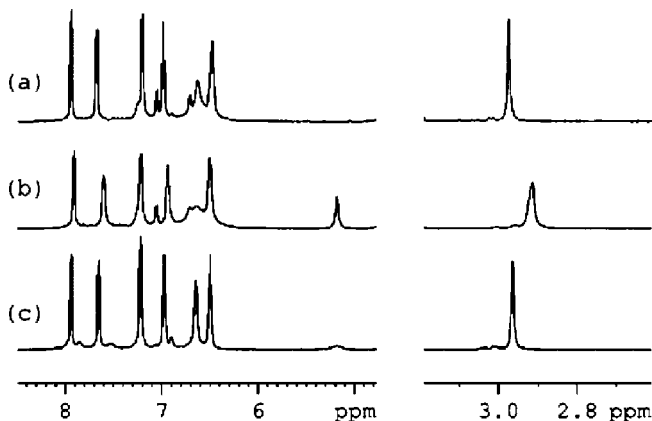


Figure 4. ¹H NMR spectra in D₂O of (a) the [Ga₄L₆]^{12−} assembly + 1 equiv. **4**; (b) + 2 equiv. **4**; (c) sample in spectrum b after 20 h

After 20 h in solution (Figure 4, c), the encapsulated tropylium signal is still sharp, while the signal for the tropylium associated with the assembly was noticeably broadened, and the signal for free tropylium at $\delta = 6.45$ ppm is unobservable. Free tropylium completely decomposes in D₂O after approximately 24 h, so it seems that encapsulation of this cation in the hydrophobic environment of the [Ga₄L₆]^{12−} cavity has significantly increased its stability.^[26] The small aromatic peaks at $\delta = 7.05$ and 6.70 ppm in Figure 4 (a, b) are most likely from tropylium decomposition products as reported by Oda et al.^[27] When the same experiments were repeated in CD₃OD, the tropylium ion reacted with the solvent to give the methoxyl adduct before encapsulation could occur (data not shown).

Conclusion

In summary, four reactive aromatic cations, which differ in geometry and hydrophobicity, have been tested as potential guest molecules inside the [Ga₄L₆]^{12−} assembly. Of the

three diazonium cations examined, only the 4-(diethylamino)benzenediazonium cation **1** is encapsulated by the supramolecular host. The spectra indicate that the small, aromatic tropylium cation, in addition to being a good guest, is involved in ion-pair interactions with the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly. Decomposition of the diazonium cation **1** and the tropylium cation **4** by solvolysis is slowed by encapsulation. The observed encapsulation of the reactive tropylium and diazonium cations is another example of the possibilities of new chemistry within the $[\text{Ga}_4\text{L}_6]^{12-}$ cluster, a “nanoscale flask,” which provides a protective environment for reactive cation guests.

Experimental Section

^1H NMR spectra were obtained with a DRX-500 spectrometer at 500 MHz. Chemical shifts for ^1H NMR spectra are referenced to the solvent resonance and reported in ppm (δ) relative to SiMe_4 . $\text{Ga}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$ and tetrafluoroborate salts of the cations 4-(diethylamino)benzenediazonium (**1**) and 4-methoxybenzenediazonium (**2**), and tropylium tetrafluoroborate (**4**) were purchased from Aldrich and used as received. 4-Chloro-2-methoxybenzenediazonium chloride was purchased from Aldrich and further purified prior to use. Unless otherwise noted, the $\text{K}_{12}\text{Ga}_4\text{L}_6$ assembly was synthesized using $\text{Ga}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$ as the gallium source.

Purification of 4-Chloro-2-methoxybenzenediazonium Chloride (Diaz Red RC, **3):** The diazonium compound **3** as purchased from Aldrich contained ZnCl_2 as a stabilizing agent. Because this ZnCl_2 caused precipitation of the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly, it was necessary to purify this compound before use. To obtain pure **3**, the diazonium chloride was dissolved in water, K_2CrO_4 was added, and the yellow ZnCrO_4 precipitate was filtered. To the remaining solution, NaBF_4 was added, and the fluoroborate salt of **3** was obtained as a white precipitate, filtered, and dried under vacuum.

Synthesis of $\text{K}_{12}\text{Ga}_4\text{L}_6$ from $\text{Ga}(\text{NO}_3)_3$: The tetrahedral assembly $\text{K}_{12}\text{Ga}_4\text{L}_6$ was synthesized as described previously,^[25] using 1.5 equiv. $\text{Ga}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$ as the gallium source. The reaction mixture was stirred for 4 h in methanol, and the volume of the pale yellow solution was reduced to < 1 mL under N_2 . Diethyl ether (≈ 30 mL) was added to precipitate the assembly, and the yellow-green precipitate was collected by centrifugation and dried under vacuum overnight. The assembly formed using this method is more sensitive to oxidation in solution than the assembly formed from $\text{Ga}(\text{acac})_3$. Yield: 84 mg (MW ≈ 3650 ; 94%).

Addition of Diazonium Cations to the $[\text{Ga}_4\text{L}_6]^{12-}$ Assembly: The tetrafluoroborate salts of the diazonium cations (**1–3**, 0.5 and 1 equiv.) in either D_2O or CD_3OD solutions were added to solutions of $\text{K}_{12}\text{Ga}_4\text{L}_6$ (0.5 mL, 5 mM) in D_2O or CD_3OD . Of these three diazonium cations, only the 4-(diethyldiamino)benzenediazonium cation was encapsulated as a guest molecule. NMR signals are reported for the encapsulated species only.

[4-(Diethylamino)benzenediazonium (1**) \subset Ga_4L_6] $^{11-}$:** ^1H NMR (ppm): $\delta = 7.92$ (d, $J = 7.0$ Hz, Ar_NH), 7.69 (d, $J = 8.0$ Hz, Ar_NH), 7.19 (d, $J = 7.8$ Hz, Ar_CH), 6.98 (t, $J = 8.0$ Hz, Ar_NH), 6.61 (d, $J = 7.3$ Hz, Ar_CH), 6.51 (t, $J = 7.5$ Hz, Ar_CH), 3.95 (d, $J = 12$ Hz, guest aromatic H), 0.37 (q, $J = 6.5$ Hz, guest CH_2), 0.05 (q, $J = 6.5$ Hz, guest CH_2), -1.10 (t, $J = 6.5$ Hz, guest CH_3).

Addition of the Tropylium Cation to the $[\text{Ga}_4\text{L}_6]^{12-}$ Assembly: ^1H NMR experiments were carried out in 5 mM solutions (0.5 mL) of ether-precipitated $\text{K}_{12}\text{Ga}_4\text{L}_6$ in D_2O . Equivalents of $[\text{C}_7\text{H}_7][\text{BF}_4]$ were added from a freshly-prepared solution in D_2O . Experiments in CD_3OD were not possible due to the reactivity of the tropylium cation. NMR signals are reported for the encapsulated species only. When more than one equivalent of tropylium cation was added the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly, a second broad signal at $\delta = 5.18$ ppm in the ^1H NMR spectrum was observed. This signal is attributed to tropylium cation associated with the outside of the assembly, and causes the encapsulated tropylium signal to broaden and shift slightly upfield.

$[\text{C}_7\text{H}_7 \subset \text{Ga}_4\text{L}_6]^{11-}$: ^1H NMR (ppm): $\delta = 7.93$ (d, $J = 7.7$ Hz, Ar_NH), 7.65 (d, $J = 8.5$ Hz, Ar_NH), 7.22 (d, $J = 8.0$ Hz, Ar_CH), 6.97 (t, $J = 8.2$ Hz, Ar_NH), 6.64 (br. s, Ar_CH), 6.50 (t, $J = 7.7$ Hz, Ar_CH), 2.95 (s; tropylium H).

Acknowledgments

This research was supported by NSF grant CHE0074319. We also thank the NIH for a postdoctoral fellowship to J. L. B. and the Alexander von Humboldt Foundation for a fellowship to M. M. We thank Anna Davis and Dorothea Fiedler for editing assistance.

- [1] J.-M. Lehn, *Supramolecular Chemistry*, VCH Verlagsgesellschaft, Weinheim, **1995**.
- [2] J. Rebek, *Accounts Chem. Res.* **1999**, *32*, 278–286.
- [3] J. P. Sauvage, *Accounts Chem. Res.* **1998**, *31*, 611–619.
- [4] D. L. Caulder, K. N. Raymond, *J. Chem. Soc., Dalton Trans.* **1999**, 1185–1200.
- [5] R. M. Yeh, A. V. Davis, K. N. Raymond, In *Comprehensive Coordination Chemistry II*, (Eds.: M. Fujita, A. Powell, Creutz, A.), Elsevier Ltd., **2003**, pp. 327–355.
- [6] J. M. Kang, J. Rebek, *Nature* **1997**, *385*, 50–52.
- [7] M. Fujita, N. Fujita, K. Ogura, K. Yamaguchi, *Nature* **1999**, *400*, 52–55.
- [8] M. Ziegler, J. L. Brumaghim, K. N. Raymond, *Angew. Chem. Int. Ed.* **2000**, *39*, 4119–4121.
- [9] C. Müller, J. A. Whiteford, P. J. Stang, *J. Am. Chem. Soc.* **1998**, *120*, 9827–9837.
- [10] A. R. Renslo, J. A. Rebek, *Angew. Chem. Int. Ed.* **2000**, *39*, 3281–3283.
- [11] S. Saito, C. Nuckolls, J. Rebek, *J. Am. Chem. Soc.* **2000**, *122*, 9628–9630.
- [12] M. Yoshizawa, Y. Takeyama, T. Okano, M. Fujita, *J. Am. Chem. Soc.* **2003**, *125*, 3243–3247.
- [13] S. K. Körner, F. C. Tucci, T. H. Rudkevich, J. A. Rebek, *Chem. Eur. J.* **2000**, *6*, 187–195.
- [14] D. Fiedler, D. H. Leung, R. G. Bergman, K. N. Raymond, *J. Am. Chem. Soc.* **2004**, *126*, 3674–3675.
- [15] D. Fiedler, D. Pagliero, J. L. Brumaghim, R. G. Bergman, K. N. Raymond, *Inorg. Chem.* **2004**, *43*, 846–848.
- [16] D. L. Caulder, K. N. Raymond, *Acc. Chem. Res.* **1999**, *32*, 975–982.
- [17] A. J. Terpin, M. Ziegler, D. J. Johnson, K. N. Raymond, *Angew. Chem. Int. Ed.* **2001**, *40*, 157–160.
- [18] T. N. Parac, M. Scherer, K. N. Raymond, *Angew. Chem. Int. Ed.* **2000**, *39*, 1239–1242.
- [19] D. H. Leung, D. Fiedler, R. G. Bergman, K. N. Raymond, *Angew. Chem. Int. Ed.* **2004**, *43*, 963–966.
- [20] M. Ziegler, A. V. Davis, D. W. Johnson, K. N. Raymond, *Angew. Chem. Int. Ed.* **2003**, *42*, 665–668.
- [21] A. Shivanyuk, E. F. Paulus, V. Boemer, *Angew. Chem. Int. Ed.* **1999**, *38*, 2906–2909.

- [22] M. O. Vysotsky, A. Pop, F. Broda, I. Thondorf, V. Boemer, *Chem. Eur. J.* **2001**, 7, 4403–4410.
- [23] A. Shivanyuk, J. Friese, S. Doering, J. A. Rebek, *J. Org. Chem.* **2003**, 68, 6489–6496.
- [24] Due to the reactivity of these diazonium cations with ketones, the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly was synthesized using GaNO_3 instead of $\text{Ga}(\text{acac})_3$ (acac = acetylacetonate) and precipitated with diethyl ether instead of acetone to eliminate the presence of ketones in solutions of the $[\text{Ga}_4\text{L}_6]^{12-}$ assembly.
- [25] D. L. Caulder, R. E. Powers, T. N. Parac, K. N. Raymond, *Angew. Chem. Int. Ed.* **1998**, 37, 1840–1843.
- [26] Stability of the tropylium cation was determined by monitoring a solution of $[\text{C}_7\text{H}_7][\text{BF}_4]$ in D_2O by ^1H NMR spectroscopy until the tropylium resonance at $\delta = 6.45$ ppm was no longer observed.
- [27] M. Oda, K. Okawa, H. Tsuru, S. Kuroda, *Tetrahedron* **2003**, 59, 795–800.

Received July 28, 2004