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Author

Biros, Shannon M.

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Design and Formation of a Large, Tetrahedral, Metal-ligand Cluster Using 1,1′-Binaphthyl Ligands

*Shannon M. Biros, Robert M. Yeh and Kenneth N. Raymond**

Many chemists have been fascinated with the development of discrete supramolecular structures that encapsulate guest molecules. These structures can be assembled through covalent[1,2] or hydrogen bonds,[3] electrostatic[4] or metal-ligand interactions.[5,6] These host structures have provided valuable insight into the forces involved in small molecule recognition. Our work has focused on the design and study of metal-ligand clusters of varying sizes.[7,8] The naphthalene $[M_4L_6]^{12-}$ cluster[9] **1**, shown in Figure 1, has demonstrated diastereoselective guest binding[10] and chiral induction properties[11] as well as the ability to catalyze reactions carried out inside the cavity in an enzyme-like manner.[12] However, the size of the cavity (*ca*. 300-500 Å^3) has often limited the scope of substrates for these transformations.[13]

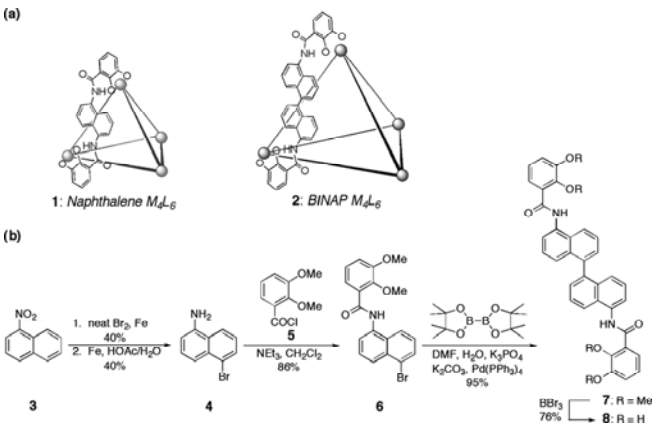

Figure 1. (a) Schematic diagrams of reported naphthalene M_4L_6 cluster **1** and new. larger binapth assembly **2**; (b) synthesis of binapth ligand **8**.

In searching for new ligands for the construction of larger M_4L_6 tetrahedra, we explored the derivatization of the 1,1'-binaphthalene (binaph) core (Figure 1). When substituted in the 5,5′ positions with catecholamides (**8**), the 1,1′-binaphthalene unit, in the pseudo-C_{2h} conformation, achieves optimal relative positioning of the chelating groups for formation of a M_4L_6 tetrahedron. This *bis*-catecholate ligand is approximately 6.7 Å longer than the original naphthalene ligand used to form cluster **1**, resulting in a calculated cavity size of at least 700 Å^3.[14]

The synthesis of *bis*-catecholate ligand **8** was accomplished in the modular manner shown in Figure 1. Selective bromination of nitronaphthalene **3** followed by reduction with iron in acetic acid gives the mono-amine **4**. Acylation with the acid chloride of 2,3-dimethoxybenzoic acid **5** provides the aryl bromide **6** in good yield. This aryl bromide can be dimerized efficiently under modified Suzuki conditions and globally deprotected using BBr_3 to give the final product **8**.

In the case of the naphthalene-based cluster **1**, the assembly can be prepared at room temperature and in the absence of guest due to the rigid nature of the host ligands. The cavity of this "empty" cluster is likely filled with solvent. Not surprisingly, with the binapth ligand **8**, cluster formation requires both heating (due to the additional six freely rotatable bonds) and the presence of a suitable guest to thermodynamically template the assembly. While looking for initial guests for this system, tetraalkylammonium salts were chosen due to a readily available range of sizes and compatibility with supramolecular assemblies.[3,7,8] The thin, outer layer of positive charge on these salts is highly complementary to the electron rich interior surface of the cluster's aromatic walls. Dissolution of ligand **8** (6 equiv.) in methanol with an excess of R_4NBr, base (KOH) and $Ga(acac)_3$ (4 equiv.) followed by heating provides the desired binapth Ga_4L_6 host-guest complexes. The ^{1}H NMR spectra of these complexes are shown in Figure 2.

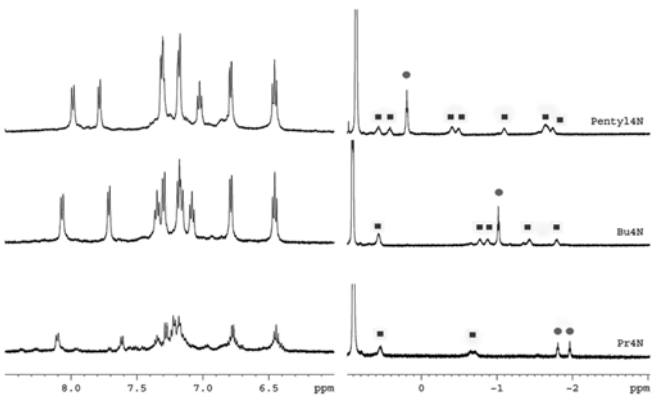

Figure 2. Upfield and host ligand portions of the ^{1}H NMR spectra (500 MHz, CD_3OD) of binapth Ga_4L_6 complexes with a series of tetraalkyammonium salts as guests: Pr_4N^+, Bu_4N^+ and *n*-pentyl$_4N^+$; (●):CH_3 and (■):CH_2 groups of bound guest.

[*] S.M. Biros, R.M. Yeh, K.N. Raymond
Department of Chemistry
University of California, Berkeley
California 94720-1460
Fax: (+1) 510-486-5283
E-mail: raymond@socrates.berkeley.edu
Homepage: www.cchem.berkeley.edu/knrgrp/home.html

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Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

The host-guest assemblies formed from the binapth ligands and the tetraalkylammonium salts Pr_4N^+, Bu_4N^+ and *n*-pentyl$_4N^+$ are readily soluble in methanol and, to a lesser extent, water. As expected, the resonances corresponding to bound guest are shifted upfield ($\Delta\delta$ ~3 ppm) in response to the shielding effect of the aromatic ligands of the host. Integration of the ^{1}H NMR spectra indicates that the host-guest complexes have a stoichiometry of six binapth ligands to one interior (bound) R_4N^+ to six exterior (free) R_4N^+ cations. These exterior ions are likely involved in cation-π interactions with the aromatic faces of each ligand.[9] The presence of peaks for both free and bound guest in the ^{1}H NMR spectra show that these complexes are kinetically stable on the NMR time scale. Cation-π[15] and CH-π interactions between host and guest as well as desolvation effects likely contribute favorably to host-guest complex formation.

Binapth Ga_4L_6 complexes containing Bu_4N^+ and *n*-pentyl$_4N^+$, respectively, show nine resonances in the aromatic region of the ^{1}H NMR spectrum corresponding to the host hydrogen atoms (Figure 3). This indicates that the complex has overall *T* symmetry with each gallium center within the complex having the same configuration, much like its naphthalene predecessor. The complex with Pr_4N^+ as a guest shows nine groups of aromatic resonances in this region, although in this case there is some degree of asymmetry between each ligand. This is likely a factor resulting from the ligands "puckering" in toward the cavity to maximize contact with the smaller guest. This host also demonstrates size selectivity: Et_4N^+ is too small to efficiently template the Ga_4L_6 assembly, while *n*-hexyl$_4N^+$ is too large.

Further analysis of the ^{1}H NMR spectra of these complexes reveals information about the conformation of bound guest. As the guest alkyl chain length increases from propyl to pentyl, the resonance corresponding to the methyl group progressively shifts downfield. This indicates a coiling of the alkyl chains toward the center of the cavity as the size of the guest increases.[16] Diastereotopic splitting of the geminal methylene proton resonances of the bound guest is also observed, indicating that the host cavity is chiral in nature.

Further evidence for host-guest complex formation can be shown through 2D NOESY experiments (Figure 3). For the $[Bu_4N^+ \subset \text{binapth } M_4L_6]^{11-}$ complex (where ⊂ denotes encapsulation), strong NOE cross peaks are observed between the guest alkyl resonances and the aromatic protons of the host ligands. This indicates close through space contacts between host and guest, concurrent with a stable, host-guest complex.

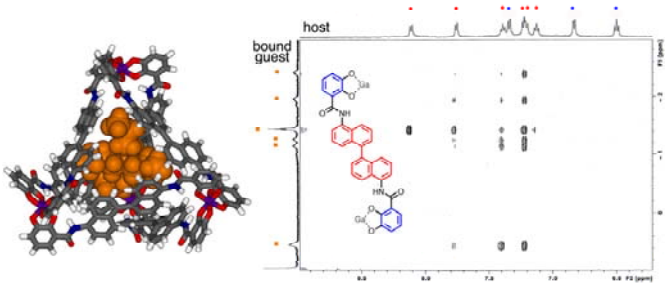

Figure 3. (Left) Minimized structure (host: CPK colors, guest: orange CPK spheres; CAChe, v. 6.1, MM3) and (Right) 2D NOESY (500 MHz, CD_3OD) of $[Bu_4N^+ \subset \text{binapth } Ga_4L_6]^{11-}$ complex.

Quaternary phosphonium salts bearing aromatic substituents are also suitable guests for this host. Triphenylpropyl-, triphenylbutyl- and tetraphenylphosphonium efficiently template the binapth Ga_4L_6 assembly. The $[Ph_4P^+ \subset \text{binapth } Ga_4L_6]^{11-}$ complex retains overall *T* symmetry (Figure 4). However, the aromatic region of the of $[Ph_3PrP^+ \subset \text{binapth } Ga_4L_6]^{11-}$ and $[Ph_3BuP^+ \subset \text{binapth } Ga_4L_6]^{11-}$ ^{1}H NMR spectra show 36 sets of resonances corresponding to the aromatic hydrogens of the host ligands. This indicates a decrease in the overall symmetry of the host-guest complex, likely resulting from a hindered rotation of the C_3 symmetric guest inside the host's cavity. A second possible explanation for these complex ^{1}H NMR spectra is that a different host-guest assembly is forming in the presence of a non-ideal guest for the Ga_4L_6 structure. These theories are difficult to prove without x-ray structural data, however high resolution mass spectra of these complexes (*vide infra*) supports the formation of a complex with $Ga_4L_6(R_4P^+)$ stoichiometry.

The host-guest complexes were further analyzed using high resolution ESI-QTOF mass spectrometry. The identity of these complexes can be readily confirmed by their complex isotopic pattern at various charge states. For instance, the predicted *m/z* peak for the $[(Bu_4N^+)(5K^+)(Bu_4N^+ \subset Ga_4L_6)]^{5-}$ complex is 854.778, and the observed value is 854.779. The predicted isotopic splitting pattern of this peak is also in excellent agreement with the experimental data (see supporting information).

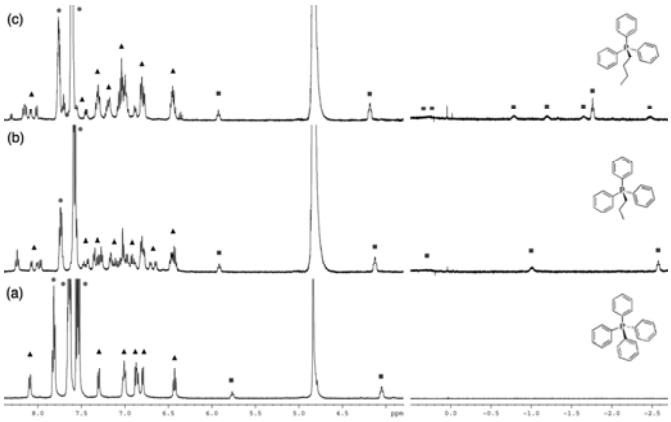

Figure 4. Aromatic and upfield regions of ^{1}H NMR spectra (500 MHz, CD_3OD) of binapth Ga_4L_6 complexes with quaternary phosphonium guests: (a) Ph_4P^+, (b) Ph_3PrP^+ and (c) Ph_3BuP^+; (●): free guest, (■): bound guest (one bound guest resonance for each complex is beneath the solvent peak at 4.8) (▲): host resonances.

Summary and outlook. We have utilized a *bis*-catecholate-1,1′-binaphthalene ligand to form a novel, self-assembled Ga_4L_6 metal-ligand cluster. This host binds larger guests than previous assemblies we have reported. Future work will explore guest scope, the compatibility of host formation with varying metal centers and the dynamics of guest exchange. In addition, the larger cavity will be exploited to facilitate reactivity.

Binapth ligand synthesis and Host-Guest Assembly Formation: Detailed procedures and characterization data for the preparation of compounds **4**, **6**, **7**, **8** and all Ga_4L_6-guest complexes can be found in the supporting information.

Keywords: supramolecular chemistry · chiral recognition · metal-ligand assembly ·

[1] F. Diederich, *Cyclophanes: Monographs in Supramolecular Chemistry*, The Royal Society of Chemistry, Cambridge, UK, **1991**.
[2] D. J. Cram, *Container Molecules and Their Guests, Vol. 4*, Royal Society of Chemistry, Cambridge, **1994**.
[3] F. Hof, S. L. Craig, C. Nuckolls, J. Rebek, Jr., *Angew. Chem. Int. Ed.* **2002**, *41*, 1488.
[4] F. Corbellini, R. M. A. Knegtel, P. D. J. Grootenhuis, M. Crego-Calama, D. N. Reinhoudt, *Chem. Eur. J.* **2005**, *11*, 298.
[5] M. A. Pitt, D. W. Johnson, *Chem. Soc. Rev.* **2007**, *9*, 1441.
[6] M. Fujita, M. Tominaga, A. Hori, B. Therrien, *Acc. Chem. Res.* **2005**, *38*, 371.
[7] D. L. Caulder, K. N. Raymond, *Acc. Chem. Res.* **1999**, *32*, 975.
[8] D. W. Johnson, K. N. Raymond, *Inorg. Chem.* **2001**, *40*, 5157.
[9] D. L. Caulder, R. E. Powers, T. N. Parac, K. N. Raymond, *Angew. Chem. Int. Ed.* **1998**, *37*, 1840.
[10] D. Fiedler, D. H. Leung, R. G. Bergman, K. N. Raymond, *J. Am. Chem. Soc.* **2004**, *126*, 3674.
[11] D. H. Leung, D. Fiedler, R. G. Bergman, K. N. Raymond, *Angew. Chem. Int. Ed.* **2004**, *43*, 963.
[12] M. D. Pluth, R. G. Bergman, K. N. Raymond, *Science* **2007**, *316*, 85.
[13] D. H. Leung, R. G. Bergman, K. N. Raymond, *J. Am. Chem. Soc.* **2007**, *129*, 2746.
[14] Cavity volume calculations were carried out using *Voidoo* with a 1.4Å diameter rolling ball on a minimized calculated structure (CAChe) of the binapth Ga4L6 assembly. (a) Kleywegt, G.J.; Zou, J.Y.; Kjeldgaard, M.; Jones, T.A. *International Tables for Crystallography*; Springer, 2001; Vol. F; (b) Kleywegt, G.J.; Jones, T.A. *Acta Cryst.* **1994**, *D50*, 178-185.
[15] J. C. Ma, D. A. Dougherty, *Chem. Rev.* **1997**, *97*, 1303.
[16] L. C. Palmer, J. Rebek, Jr., *Org. Lett.* **2005**, *7*, 787.
[17] L. H. Klemm, J. W. Sprague, E. Y. K. Mak, *J. Org. Chem.* **1957**, *22*, 161.