Structure and Small Molecule Binding of a Tetranuclear Iron(II) Resorc[4]arene-Based Cage Complex

O. Danny Fox, N. Kent Dalley, and Roger G. Harrison*

Department of Chemistry and Biochemistry, Brigham Young University, Provo, Utah 84602

Received July 14, 1999

Four iron(II) ions help assemble a container molecule (**1**), by bringing together two hemispherical resorc[4]arenes. The resorc[4]arene ligands are appended with four iminodiacetate moieties which act as ligands for the iron atoms. X-ray crystallographic analysis of **1** shows that the iron atoms are coordinated in an *N,N-cis-fac* manner and exhibit a trigonal prismatic geometry. When **1** is formed in water, six water molecules, hydrogen bonded together, occupy its cavity. However, when **1** is formed with bromobenzene present in the water solution, bromobenzene is trapped in the cavity. Multinuclear NMR experiments (^{1}H, ^{2}H, and ^{19}F) demonstrate the pH-dependent encapsulation of various organic guest molecules by **1**, e.g., substituted benzenes, alkanes, ethers, and chlorocarbons. Complex **1** is the first iron(II)-containing cage complex that is formed by assembly of resorcinarene molecules and that binds neutral organic molecules.

Introduction

Molecular recognition of cations, anions, and, to a lesser extent, neutral molecules by synthetic complexes has been achieved with a diverse array of metal-assembled molecular architectures.[1] Several of these metal assemblies can be classified as cage complexes since they possess a cavity within the framework of the complex.[2] Calixarenes and resorcinarenes have been used as templates for the synthesis of some of the metal cage complexes, due to their cup-shaped structure and their ability to be functionalized with metal-coordinating ligands.[2a−c] The features that make certain metal ions suitable for the formation of supramolecules such as redox stability and coordination saturation can also make them unsuitable for further reactivity.[3] It is then understandable why few reports have been published on the use of redox-active iron(II) to assemble molecular cages and why it has not been used in supramolecules that host neutral guests.[4]

The redox chemistry of iron and its ubiquitous presence within organisms has created tremendous interest in the chemistry of iron complexes.[5] Metalloproteins that contain iron have a molecular recognition site, along with a reactive metal center. The selective substrate binding and reactivity observed in iron-containing enzymes is difficult to duplicate with synthetic complexes.[6] Various iron complexes have been synthesized with amine, pyridyl, phenolic, and carboxylate donor moieties, to structurally model the amino acid binding sites present in nonheme iron proteins.[7] In particular, carboxylate ligands have been used to model both enzyme systems that oxidize organic molecules and proteins responsible for iron storage. In both cases, structural analogues have been synthesized, and in some instances the oxidative properties of the complexes toward organic molecules (including DNA) have been studied.[8]

In pursuit of an iron(II)-containing complex that has a molecular recognition site, we have synthesized and characterized a tetranuclear iron(II) cage complex (**1**) based on a resorc[4]arene ligand. X-ray crystallography of single crystals of **1** show that it is capable of encapsulating water and organic molecules. Even though **1** is paramagnetic, NMR studies show it is able to bind and release small neutral organic molecules as

---

* To whom correspondence should be addressed. Phone: (801) 378-8096. Fax: (801) 378-5474. E-mail: roger_harrison@byu.edu.

(1) (a) Baxter, P. N. W. In *Comprehensive Supramolecular Chemistry*; Sauvage, J. P., Hosseini, M. W., Eds.; Pergamon: Oxford, 1996; Vol. 9, p 165 and references therein. (b) Linton, B.; Hamilton, A. D. *Chem. Rev.* **1997**, *97*, 1669.

(2) (a) Ikeda, A.; Yoshimura, M.; Udzu, H.; Fukuhara, C.; Shinkai, S. *J. Am. Chem. Soc.* **1999**, *121*, 4296. (b) Fox, O. D.; Dalley, N. K.; Harrison, R. G. *J. Am. Chem. Soc.* **1998**, *120*, 7111. (c) Dalcanale, E.; Jacopozzi, P. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 613. (d) Fleming, J. S.; Mann, K. L.; Carraz, C.-A.; Psillakis, E.; Jeffery, J. C.; McCleverty, J. A.; Ward, M. C. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 1279. (e) Caulder, D. L.; Powers, R. E.; Parac, T. N.; Raymond, K. N. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 1840. (f) Fujita, M.; Yu, S.-Y.; Kusukawa, T.; Funaki, J.; Ogura, K.; Yamaguchi, K. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 2082. (g) Saalfrank, R. W.; Seitz, V.; Caulder, D. L.; Raymond, K. N.; Teichert, M.; Stalke, D. *Eur. J. Inorg. Chem.* **1998**, 1313.

(3) (a) Sanders, J. K. M. *Chem. Eur. J.* **1998**, *4*, 1378. (a) Jones, C. J. *Chem. Soc. Rev.* **1998**, *27*, 289. (b) Canary, J. W.; Gibb, B. C. In *Progress in Inorganic Chemistry*; Karlin, K. D., Ed.; John Wiley & Sons: New York, 1997; pp 1−82.

(4) (a) Hasenknopf, B.; Lehn, J.-M.; Kneisel, B. O.; Baum, G.; Fenske, D. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1838. (b) Saalfrank, R. W.; Trummer, S.; Krautscheid, H.; Schunemann, V.; Trautwein, A. X.; Hien, S.; Stadler, C.; Daub, J. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2206.

(5) (a) Que, L. Jr.; Ho, R. Y. N. *Chem. Rev.* **1996**, *96*, 2607. (b) Feig, A. L.; Lippard, S. J. *Chem. Rev.* **1994**, *94*, 759. (c) *Cytochrome P-450: Structure, Mechanism and Biochemistry*; Ortiz de Montellano, P. R., Ed.; Plenum: New York, 1986.

(6) (a) Breslow, R.; Zhang, X.; Huang, Y. *J. Am. Chem. Soc.* **1997**, *119*, 4535. (b) *Models in Inorganic Chemistry*; Eichhorn, G. L., Marzilli, L. G., Eds.; PTR Prentice-Hall: New York, 1994. (c) Barton, D. H. R.; Doller, D. *Acc. Chem. Res.* **1992**, *25*, 504.

(7) (a) Mizoguchi, T. J.; Lippard, S. J. *J. Am. Chem. Soc.* **1998**, *120*, 11022. (b) Nivorozhkin, A. L.; Anxolabéhère-Mallart, E.; Mialane, P.; Cavydov, R.; Guilhem, J.; Cesario, M.; Audière, J.-P.; Girerd, J.-J.; Styring, S.; Schussler, L.; Seris, J.-L. *Inorg. Chem.* **1997**, *36*, 846. (c) Lambert, E.; Chabut, B.; Chardon-Noblat, S.; Deronzier, A.; Chottard, G.; Bousseksou, A.; Tuchagues, J.-P.; Laugier, J.; Bardet, M.; Latour, J.-M. *J. Am. Chem. Soc.* **1997**, *119*, 9424. (d) Bossek, U.; Hummel, H.; Weyhermüller, T.; Bill, E.; Wieghardt, K. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2642. (e) Dong, Y.; Fujii, H.; Hendrich, M. P.; Leising, R. A.; Pan, G.; Randall, C. R.; Wilkinson, E. C.; Zang, Y.; Que, L. Jr., Fox, B. G.; Kauffmann, K.; Münck, E. *J. Am. Chem. Soc.* **1995**, *117*, 2778. (f) Kato, M.; Yamada, Y.; Ingaki, T.; Mori, W.; Sakai, K.; Tsubomura, T.; Sato, M.; Yano, S. *Inorg. Chem.* **1995**, *34*, 2645. (g) Krebs, B.; Schepers, K.; Bremer, B. *Inorg. Chem.* **1994**, *33*, 1907. (h) Heath, S. L.; Powell, A. K. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 191.

10.1021/ic990834m CCC: $18.00

a function of pH. Complex **1** combines the molecular recognition and host properties of carcerand molecules[9] and the chemical properties of an iron(II) carboxylate complex.

Experimental Section

General Procedures. All commercial reagents were used as supplied. A Perkin-Elmer Plasma II inductively coupled plasma (ICP) emission spectrometer was used for ICP results. ^1H (300 and 500 MHz) NMR chemical shifts are reported in parts per million and were obtained using Varian spectrometers. Elemental analyses were performed by M-H-W Laboratories, Arizona.

Synthesis of $Sr_4[Fe_4L_2(H_2O)_6]$, $Sr_4\mathbf{1}\cdot 6H_2O$. A solution of $Ba_4L\cdot 24H_2O$ (50 mg, 0.023 mmol)[2b] in 1 M hydrochloric acid (1 mL) and water (3 mL) is made, and to it is added potassium sulfate (25 mg, 0.14 mmol), with stirring. The precipitate of barium sulfate is removed by filtration, strontium chloride (75 mg, 0.29 mmol) added, and the precipitate of strontium sulfate removed by filtration. L-Ascorbic acid (40 mg, 0.23 mmol) and iron(II) chloride monohydrate (13 mg, 0.090 mmol) are then added to the solution. While the solution is stirred, its pH is raised to 5 by addition of finely ground potassium carbonate. The solution is filtered into a test tube, layered with 2-propanol, covered, and allowed to stand for 3 days, after which colorless crystals are formed (29 mg, 67%). On exposure to air, the crystals quickly lose solvent and turn yellow in color. The solution generally remains colorless during the raising of pH, although a very faint purple coloration is sometimes observed. ^1H NMR chemical shifts of the potassium salt[10] of **1** without organic guest present (500 MHz, D_2O, 22 °C, HDO = 4.80 ppm): $\delta = 135, 124, 65, 26, 6.45, 6.12, 5.23, 5.08, 4.60, 1, -7.50, -12.23, -13.12, -13.47, -19$. Analysis of crystals of $Sr_4\mathbf{1}\cdot 6H_2O$ by ICP confirmed the presence of both strontium and iron in a 1:1 molar ratio. Anal. Calcd for $C_{112}H_{104}Fe_4N_8O_{48}Sr_4\cdot 44H_2O$: C, 36.39; H, 5.24; N, 3.03. Found: C, 36.28; H, 4.36; N, 2.95.

Synthesis of $Sr_4[Fe_4L_2\cdot C_6H_5Br]$, $Sr_4\mathbf{1}\cdot C_6H_5Br$. $Sr_4\mathbf{1}\cdot C_6H_5Br$ is synthesized in the same manner as $Sr_4\mathbf{1}\cdot 6H_2O$ except that the solution is split in half after the iron(II) chloride is added and 0.25 mL of bromobenzene is added to half of it. The solution containing bromobenzene is stirred for 30 min before the pH is raised. The solution is then layered with 2-propanol, covered, and allowed to stand for 2 days, after which time colorless crystals are formed (15 mg, 69%). Host ^1H NMR chemical shifts of the potassium salt of $\mathbf{1}\cdot C_6H_5Br$ (500 MHz, D_2O, 22 °C, HDO = 4.80 ppm): $\delta = 134, 121, 59, 34, 6.26, 5.87, 5.32, 4.65, 4.50, 3$ (very broad) $-5.82, -10.6, -13.3, -14.6, -19$ (very broad). Analysis of crystals of $Sr_4\mathbf{1}\cdot C_6H_5Br$ by ICP confirmed the presence of both strontium and iron in a 0.9:1 molar ratio. Anal. Calcd for $C_{112}H_{104}Fe_4N_8O_{48}Sr_4\cdot C_6H_5Br\cdot 50H_2O$: C, 35.77; H, 5.31; N, 2.83. Found: C, 35.85; H, 3.53; N, 2.67.

Solution Encapsulation Studies. To a stirred solution of $Ba_4L\cdot 24H_2O$ (50 mg, 0.0233 mmol) in 1 M hydrochloric acid (1 mL) and water (3 mL) is added potassium sulfate (25 mg, 0.14 mmol). The precipitate of barium sulfate that forms is removed by filtration.[10] Iron(II) chloride monohydrate (13 mg, 0.090 mmol) is then added to the solution. The solution is split into two equal halves, a sample of organic compound (0.25 mL) is added to each half, and the solutions are stirred for 30 min. The solutions are then degassed three times by freeze−thaw methods and left under nitrogen. While the solutions are stirred under nitrogen, their pH values are raised by adding a degassed potassium carbonate solution by syringe. After pH 5 is reached, the solutions are vacuumed to dryness and the remaining residue is dissolved in degassed D_2O. The D_2O solutions are transferred by syringe to gas-tight NMR tubes.

Table 1. Crystal Data and Structure Refinement for $Sr_4\mathbf{1}\cdot 6H_2O$ and $Sr_4\mathbf{1}\cdot C_6H_5Br$

compd	$Sr_4\mathbf{1}\cdot 6H_2O$	$Sr_4\mathbf{1}\cdot C_6H_5Br$
empirical formula	$C_{112}H_{216}Fe_4N_8O_{104}Sr_4$	$C_{112}H_{188.43}BrFe_{4.6}N_8O_{90.2}Sr_{3.4}$
fw	3912.8	3725.06
space group	$I4_1/a$	$I4_1/a$
a (Å)	19.8952(11)	19.822(4)
b (Å)	19.8952(11)	19.822(4)
c (Å)	54.545(7)	54.34(2)
α, β, γ (deg)	90	90
V (Å^3)	21 590(3)	21 351(10)
Z	4	4
ρ_{calcd} (g cm^{-3})	1.204	1.159
μ(Mo Kα) (mm^{-1})	1.329	1.413
T (K)	293(2)	293(2)
λ (Å)	0.710 73	0.710 73
R1 $[I > 2\sigma(I)]^a$	0.0953	0.1011
wR2^b	0.2399	0.2487

^{a} $R1 = \sum||F_o - F_c||/\sum|F_o|$. ^{b} $wR2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum[w(F_o^2)^2]\}^{1/2}$.

X-ray Structural Determination. Crystal data and details of data collection are given in Table 1. In addition, the Supporting Information contains crystallographically determined parameters. The crystals of $Sr_4\mathbf{1}\cdot 6H_2O$ and $Sr_4\mathbf{1}\cdot C_6H_5Br$ rapidly lose solvent when removed from their mother liquor, and therefore the X-ray data collections were performed on a crystal glued to the wall of a sealed glass capillary containing the mother liquor. The data were collected using a Bruker P4 automated diffractometer with graphite-monochromated Mo Kα radiation ($\lambda = 0.710\ 73$ Å). Lattice parameters were calculated using a least-squares procedure involving carefully centered reflections. The solution and refinement were carried out using the SHELXTL PC program package.[11] Colorless diamond-shaped crystals of $Sr_4\mathbf{1}\cdot 6H_2O$ (0.54 × 0.35 × 0.25 mm) and $Sr_4\mathbf{1}\cdot C_6H_5Br$ (0.5 × 0.3 × 0.3 mm) were used for the structural studies. Both compounds crystallized in the tetragonal space group I_1/a with essentially identical unit cell parameters (see Table 1). Of the 6084 reflections collected for $Sr_4\mathbf{1}\cdot 6H_2O$, 5675 were unique ($R_{int} = 0.0689$) and refined with 542 parameters and no restraints. Of the 5424 reflections collected for $Sr_4\mathbf{1}\cdot C_6H_5Br$, 4910 were unique ($R_{int} = 0.0742$) and refined with 527 parameters. In both structures, the asymmetric unit contains water molecules, but it is difficult to select which peaks in the difference maps are water molecules as some sites may be only partially occupied. Electron densities that were more than one electron per cubic angstrom and within hydrogen bonding distance of an oxygen were assigned as oxygen. Absorption (Ψ scans) and diffuse solvent molecule corrections were applied to the data for $Sr_4\mathbf{1}\cdot 6H_2O$. Partial structures were obtained using direct methods, and the structures were completed using Fourier methods. The non-hydrogen atoms of the host molecules and most of the water molecules were refined anisotropically. The positions of hydrogen atoms bound to carbon atoms for the complexes were calculated, and the hydrogen atoms were allowed to ride on their neighboring carbon atoms during the refinement. The position of the bromine from bromobenzene could be found within the cavity; however, the phenyl group of bromobenzene was seen as electron density in several places within the cavity due to its high degree of disorder. In both structures, the countercation was disordered, with the occupancy parameters in both structures approximately 0.85 and 0.15. In $Sr_4\mathbf{1}\cdot 6H_2O$ both sites were occupied by Sr, but in $Sr_4\mathbf{1}\cdot C_6H_5Br$, the lower population site was occupied by iron. The atom assignment was based on ICP data, which indicated a Sr:Fe ratio of 1:1 for $Sr_4\mathbf{1}\cdot 6H_2O$ and 0.9:1 for $Sr_4\mathbf{1}\cdot C_6H_5Br$.

Results and Discussion

Complex **1** forms by combining iron(II) chloride with the iminodiacetic acid-functionalized resorc[4]arene ligand, L, in aqueous solution above pH 5 under anaerobic conditions or in the presence of a reducing agent (Scheme 1). Colorless, prismatic, X-ray-quality crystals of $Sr_4\mathbf{1}\cdot 6H_2O$ form after 3 days at ambient temperature by layering isopropyl alcohol over an aqueous solution of **1**, synthesized in the presence of L-ascorbic acid and strontium chloride. The tetranuclear iron(II) anion (Figure 1) of $Sr_4\mathbf{1}\cdot 6H_2O$ is assembled by four iron(II) atoms,

---

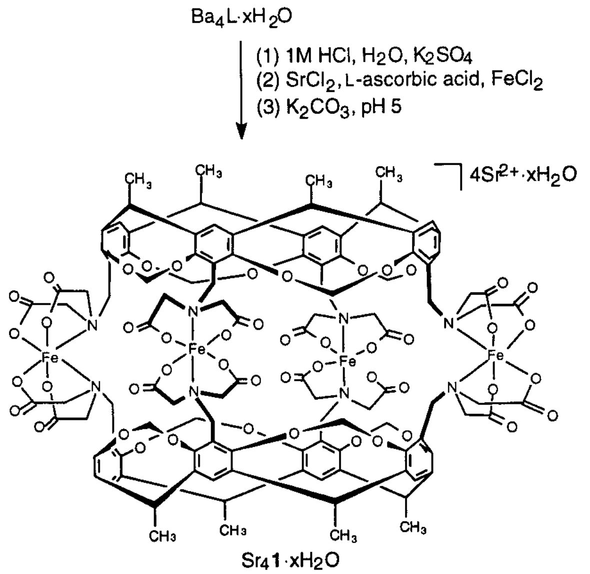
(8) (a) *Active Oxygen in Biochemistry*; Valentine, J. S., Foote, C. S., Greenberg, A., Liebman, J. F., Eds.; Chapman & Hall: New York, 1995. (b) Dervan, P. S. *Science* **1986**, *232*, 464.

(9) For structurally similar compounds without metal ions see (a) Cram, D. J.; Cram, M. J. In *Container Molecules and Their Guests, Monographs in Supramolecular Chemistry*; Stoddart, J. F., Ed.; The Royal Society of Chemistry: Cambridge, 1994. (b) Chapman, R. G.; Sherman, J. C. *J. Am. Chem. Soc.* **1998**, *120*, 9818.

(10) The potassium salt of **1** was used in the NMR studies due to its high solubility in water.

(11) Sheldrick, G. M., SHELXTL PC version 5.03, Bruker Analytical X-ray Systems, Madison, WI, 1994.

Scheme 1



which bring together two hemispherical resorc[4]arene units to form a molecular container. Although there are numerous examples of metal-coordinated calixarene molecules, **1** is only the third example of a crystallographically characterized metal cage molecule formed with calixarene or resorcinarene molecules.[2a,b]

The iron atoms in Sr_4**1**$\cdot 6H_2O$ are coordinated by two iminodiacetate moieties in an *N,N-cis fac* manner; an *N,N-trans fac* coordination would not result in the formation of the cagelike structure. Crystallographically, there is only one unique iron(II) center, and it exhibits a significant distortion from octahedral toward trigonal prismatic geometry, as indicated by the surrounding iron bond lengths and angles (Figure 1). The iron centers are in one plane and form a belt around the outside of the cavity, leaving the interior of the cavity surrounded by phenyl, ether, and hydrocarbon groups. Included within the cavity of **1** are six water molecules that form a distorted octahedron through a hydrogen-bonding network (oxygen−oxygen distances are 2.9−3.0 Å).[14] The dimensions of the octahedron of water molecules confirm that **1** is suitable in size for the inclusion of small organic molecules (e.g., benzene, THF, and hexane). The distance from the top to bottom of the cavity is 11.0 Å (methyne to methyne carbon), while the distance across the cavity is 9.71 Å (benzyl to benzyl carbon). The closest contacts between the resorcinarene halves come between the benzyl carbons which are 3.66 Å apart and the etheric carbons which are 4.75 Å apart. Thus, the portals between the etheric groups are small. Strontium countercations reside beyond the iron centers and are bound to the iron cages through weak bonds to oxygen atoms of the carboxylate groups. Water molecules complete the coordination sphere of the nine-coordinate strontium ions.

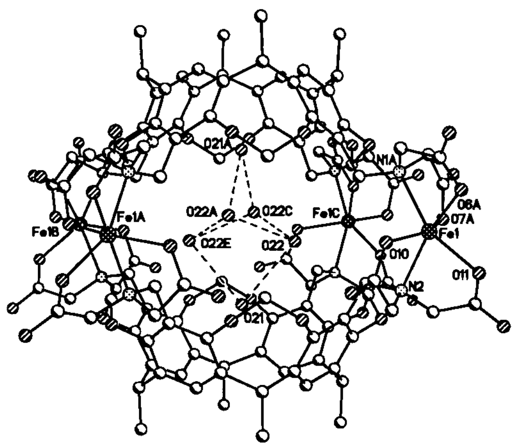


Figure 1. Structure of the octaanion of Sr_4**1**$\cdot 6H_2O$ showing the six encapsulated water molecules. Hydrogens, strontium ions, and water molecules outside of the cavity have been omitted and atoms drawn as spheres for clarity. Selected bond lengths (Å) and angles (deg): Fe1−O10, 2.102(10); Fe1−O11, 2.116(10); Fe1−N2, 2.251(11); Fe1−O6A, 2.115(11); Fe1−O7A, 2.123(11); Fe1−N1A, 2.251(11); N2−Fe1−N1A, 123.5(4); O11−Fe−N2, 75.5(4); O10−Fe1−N2, 76.5(4); O11−Fe1−O10, 111.4(4); O6A−Fe1−N1A, 75.9(4); O7A−Fe1−N1A, 75.7(4); O11−Fe1−N1A, 155.5(4); O6A−Fe1−O7A, 110.8(5).

To determine whether the cavity of **1** is suitable for encapsulation of organic molecules, solution NMR studies of **1** were done in the absence and presence of guest molecules. When the paramagnetic iron(II) ions coordinate to the resorcinarene ligand, the proton resonances of the ligand exhibit substantial isotropic shifts and line broadening.[15] The seven proton resonances in the diamagnetic region from the resorcinarene ligand become fifteen resonances upon formation of complex **1** and span 160 ppm.[16] When **1** is formed in the presence of benzene, the resorcinarene peaks move by 0.2−8 ppm from their chemical shifts when **1** is formed in water and an additional peak is observed at −15 ppm. Likewise, when **1** is formed in the presence of other organic molecules, a similar shift of resorcinarene peaks is observed and new peaks attributed to the guest arise (Table 2). Similar shifts in the ^{1}H NMR spectrum of the host are observed when deuterated and partially fluorinated molecules are encapsulated. A series of ^{2}D and ^{19}F NMR experiments showed that these nuclei also undergo substantial, upfield, isotropic shifts when held within the confines of the paramagnetic host. Extensive studies of diamagnetic host−guest carcerand and hemicarcerand complexes have shown that inclusion of a guest within a host causes resonance shifts in both the host and the guest, typically 1−4 ppm for the guest.[9] For the paramagnetic Fe−resorcinarene complex, resonance shifts for an encapsulated guest are, as expected, much larger (20−30 ppm).

The guest can easily be released by lowering the pH, which breaks the metal−ligand coordination and gives back free guest and ligand, which show resonances in the diamagnetic NMR region. CPK and computer models of **1** show the portals of **1** to be small, and molecules such as benzene and toluene cannot easily escape.

Guest molecules encapsulated by **1** give rise to two sets of proton resonances (Table 2). The ratios of the sets of peaks vary with guest and seem to become close to 1:1 with increased

---

(12) The complex **1** is isostructural with the tetranuclear cobalt(II) complex recently reported by us, ref 2b.

(13) Complexes with iminodiacetate moieties: (a) Lopez-Alcala, J. M.; Puerta, M. C.; Gonzalez-Vilchez, F. *Polyhedron* **1984**, *3*, 623. (b) Lind, M. D.; Hamor, M. J.; Hamor, T. A.; Hoard, J. L. *Inorg. Chem.* **1964**, *3*, 34. (c) Kennard, C. H. L. *Inorg. Chim. Acta* **1967**, *1*, 347. (d) Schugar, H. J.; Hubbard, A. T.; Lippard, S. J.; Schugar, H.; Walling, C. *Inorg. Chem.* **1967**, *6*, 1825. (e) Anson, F. C.; Gray, H. B. *J. Am. Chem. Soc.* **1969**, *90*, 71. (f) Balasubramanian, P. N.; Bruice, T. C. *J. Am. Chem. Soc.* **1986**, *108*, 5493.

(14) Robbins, T. A.; Knobler, C. B.; Bellew, D. R.; Cram, D. J. *J. Am. Chem. Soc.* **1994**, *116*, 111.

(15) Bertini, I.; Luchinat, C. *NMR of Paramagnetic Molecules in Biological Systems*, Benjamin Cummings: Menlo Park, CA, 1986.

(16) The 15 resonances occur due to the ΔΛΔΛ arrangement of the metal centers. Our paper on a similar cobalt resorcinarene complex (submitted for publication) explains why there are 15 peaks.

Table 2. NMR Chemical Shift (ppm) Data for Encapsulated Guest Molecules

guest	^{1}H (integration[a])	other nuclei	peak ratio[b]
benzene, C_6H_6	−15.5; −16.3		4:1
benzene-d_6, C_6D_6		^{2}H, −16	
fluorobenzene, C_6H_5F	−15.0	^{19}F, −139; −140	3:2[c]
chlorobenzene, C_6H_5Cl	−14.4(2), −16.0(1), −17.9(2); −14.4(2), −16.9(1), −18.4(2)		4:3
bromobenzene, C_6H_5Br	−14.2(2), −15.4(1), −18.1(2); −14.2(2), −16.4(1), −18.5(2)		1:1
1,4-difluorobenzene, $C_6H_4F_2$	−15.3	^{19}F, −145; −146	2:1[c]
1,2-dichloroethane, $C_2H_4Cl_2$	−15.7; −16.8		5:1
1,2-dichloroethane-d_4, $C_2D_4Cl_2$		^{2}H, −16	
diethyl ether, $C_4H_{10}O$	−16.9(3), −20.2(2); −17.4(3), −21.1(2)		2:1
THF, C_4H_8O	−18.4(1), −21.3(1); −19.6(1), −22.3(1)		3:1
ethyl acetate, $C_4H_8O_2$	−15.3(3), −18.1(2), −18.8(3); −15.8(3), −18.7(2), −19.8(3)		4:1
pentane, C_5H_{12}	−16.8(3), −21.9(2), −24.0(1); −17.2(3), −22.8(2), −24.6(1)		2:1
hexane, C_6H_{14}	−14.9(3), −21.2(2), −23.1(2); −15.5(3), −22.4(2), −24.0(2)		1:1
cyclohexane, C_6H_{12}	−22.3; −22.9		3:2
tetramethylsilane, $C_4H_{12}Si$	−23.7; −24.5		3:1

[a] Integral values are only relative to other guest resonances within each set of peaks, and some are tentative due to the broadness of the peaks. [b] The ratio of the first peak(s) to the second peak(s). [c] The peak ratio was determined by ^{19}F NMR because two peaks could not be distinguished in the proton NMR spectra.

guest size. Upon heating a host−guest complex (guest = pentane, cyclohexane, benzene, and fluorobenzene) to 70 °C, the smaller set of resonances move into the larger set. The two sets of guest peaks at ambient temperature could be due to the guest occupying two different positions within the host, the iron centers being in more than one configuration (i.e., the iron centers in a different configuration than ΔΛΔΛ), or there being more than one host−guest complex. Due to there being only one set of host peaks, we do not think the iron centers are in more than one configuration or that there is more than one host−guest complex. We also do not favor the possibility of there being encapsulated and free guest in equilibrium, for two reasons: the samples are vacuumed dry before being analyzed by NMR, which should remove free guest, and there would have to be a strong association of free guest with **1** to cause such a large upfield chemical shift of the hydrogens. We currently do not see where such an association would occur. NMR and X-ray crystallographic studies designed to understand the occurrence of two sets of peaks are underway.

Solid-state evidence for guest encapsulation was found by forming **1** in the presence of bromobenzene and allowing it to slowly crystallize. Single crystals of X-ray quality formed after 2 days of letting 2-propanol diffuse into a solution of **1**·bromobenzene. The unit cell parameters for the host−guest complex Sr_4**1**·C_6H_5Br are the same as for Sr_4**1**·$6H_2O$; however, instead of six water molecules, a disordered bromobenzene is found within the cavity of **1** (Figure 2). Bromine molecules are found in the cavity as an average of two positions, one above and one below a plane that can be drawn to include the iron atoms. They are oriented toward the bowl of phenyl groups and not toward the benzylic hydrogens. This bromine positioning is probably due to the best fit sterically for the bromobenzene and, to a small degree, to bonding between bromine and aryl groups. The difference map also shows electron density in other places in the cavity, which we attribute to the disordered phenyl group of bromobenzene. Thus, the NMR data provide more evidence for encapsulation of guest than do the X-ray data. Although the cavity of **1** is occupied by a bromobenzene, the resorcinarenes and iron atoms are very similar in structure to what they are when water occupies the cavity. The average iron−oxygen and iron−nitrogen bond lengths in Sr_4**1**·C_6H_5Br and Sr_4**1**·$6H_2O$ are similar.

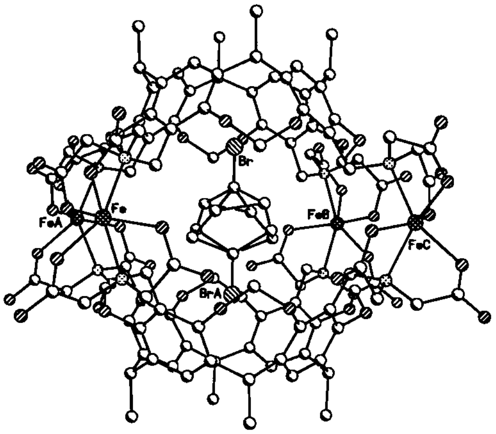


Figure 2. Structure of Sr_4**1**·C_6H_5Br showing the disordered bromobenzene as found within the cavity. The open circles within the cavity correspond to residual electron density. Strontium ions and water molecules have been omitted and atoms drawn as spheres for clarity.

In conclusion, a new tetranuclear iron(II)-assembled cage complex can be formed. And as shown by NMR spectroscopy and X-ray crystallography, the complex is capable of encapsulating organic molecules that do not contain metal-binding atoms. The chemical shifts of the encapsulated guest molecules move upfield by 20−30 ppm. To our knowledge, this is the first small, synthetic, nonheme, iron(II) complex capable of neutral guest encapsulation. Although multinuclear iron(II) complexes with mixed carboxylate- and nitrogen-containing ligands have been reported,[17] **1** is unusual because it possesses both a potentially chemically active metal ion and a cavity with molecular recognition properties. Currently, our studies are directed toward investigating the selective molecular recognition and redox properties of **1**.

Acknowledgment. We thank Brigham Young University for financial support. We thank Dr. Alexander Nazarenko for X-ray crystallography advice and Dr. Du Li for NMR spectroscopy assistance.

Supporting Information Available: Two X-ray crystallographic files in CIF format are available free of charge via the Internet at http://pubs.acs.org.

IC990834M

---

(17) (a) Herold, S.; Lippard, S. J. *J. Am. Chem. Soc.* **1997**, *119*, 145. (b) Singh, B.; Long, J. R.; Papaefthymiou, G. C.; Stavropoulos, P. *J. Am. Chem. Soc.* **1996**, *118*, 5824. (c) Laine, P.; Gourdon, A.; Launay, J. P. *Inorg. Chem.* **1995**, *34*, 5129. (d) Menage, S.; Fujii, H.; Hendrich, M. P.; Que, L., Jr. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1660. (e) Hagen, K. S.; Lachiotte, R.; Kitaygorodskiy, A. *J. Am. Chem. Soc.* **1993**, *115*, 12617.