10956 – 10962; B. Hasenknopf, J.-M. Lehn, B. O. Kneisel, G. Baum, D. Fenske, *Angew. Chem.* **1996**, *108*, 1987 – 1990; *Angew. Chem. Int. Ed. Engl.* **1996**, *35*, 1838 – 1846; O. Mamula, A. von Zelewsky, G. Bernardinelli, *Angew. Chem.* **1998**, *110*, 301 – 305; *Angew. Chem. Int. Ed.* **1998**, *37*, 290 – 293; P. L. Jones, K. J. Byrom, J. C. Jeffery, J. A. McCleverty, M. D. Ward, *Chem. Commun.* **1997**, 1361 – 1362.

[6] M. J. Hannon, C. L. Painting, W. Errington, *Chem. Commun.* **1997**, 1805 – 1806; N. W. Alcock, P. R. Barker, J. M. Haider, M. J. Hannon, C. L. Painting, Z. Pikramenou, E. A. Plummer, K. Rissanen, P. Saarenketo, *J. Chem. Soc. Dalton Trans.* **2000**, 1447 – 1461.

[7] R. F. Carina, G. Bernardinelli, A. F. Williams, *Angew. Chem.* **1993**, *105*, 1483; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1463 – 1465.

[8] E. C. Constable, A. J. Edwards, P. R. Raithby, J. V. Walker, *Angew. Chem.* **1993**, *105*, 1486; *Angew. Chem. Int. Ed. Engl.* **1993**, *32*, 1465.

[9] a) M. J. Hannon, C. L. Painting, A. Jackson, J. Hamblin, W. Errington, *Chem. Commun.* **1997**, 1807 – 1808; b) M. J. Hannon, S. Bunce, A. J. Clarke, N. W. Alcock, *Angew. Chem.* **1999**, *111*, 1353 – 1355; *Angew. Chem. Int. Ed.* **1999**, *38*, 1277 – 1278; c) M. J. Hannon, C. L. Painting, N. W. Alcock, *Chem. Commun.* **1999**, 2023 – 2024.

[10] a) Crystal structure data for $C_{50}H_{40}N_8Cu_2B_2F_8 \cdot C_2H_3N$, $M_r = 1094.65$, red plates, dimensions = $0.6 \times 0.4 \times 0.3$ mm, triclinic, space group $P\bar{1}$, $a = 16.826(3)$, $b = 17.931(2)$, $c = 18.402(3)$ Å, $\alpha = 106.351$, $\beta = 103.046(5)$, $\gamma = 102.983(5)^\circ$, $V = 4937.2(11)$ Å^3, $T = 180(2)$ K, $\lambda = 0.71073$, $Z = 4$, $\rho_{calcd} = 1.473$ Mg m^{-3}, $F(000) = 2232$, $\mu(Mo_{K\alpha}) = 0.939$ mm^{-1}. Data collected with a Siemens SMART three-circle system with CCD area detector. The crystal was held at 180(2) K with an Oxford Cryosystem Cryostream Cooler; $\theta_{max} = 29.16^\circ$. A total of 31991 reflections were measured, 22935 unique ($R_{int} = 0.0359$). Absorption correction by Psi-scan. Weighting Scheme $w = 1/(\sigma(F_0^2) + (0.0383P)^2)$, where $P = (F_0^2 + 2F_c^2)/3$. GoF on F^2 was 0.890, $R1$ (for 10956 reflections with $I > 2\sigma(I)) = 0.0537$, $wR2 = 0.1324$. Data/restraints/parameters 22935/0/1317. Largest difference Fourier peak and hole 0.907 and -0.842 e Å^{-3}. Refinement used SHELXL 97 (G. M. Sheldrick, **1997**). b) Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-146854. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB21EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

[11] a) A. Marsh, M. Silvestri, J.-M. Lehn, *Chem. Commun.* **1996**, 1527 – 1528; b) G. M. Whitesides, E. E. Simanek, J. P. Mathias, C. T. Seto, D. N. Chin, M. Mammen, D. M. Gordon, *Acc. Chem. Res.* **1995**, *1*, 37 – 44.

[12] Centroid – centroid distances of 3.84 and 4.18 Å. Shortest C – centroid distance = 3.88 Å. Shortest C – C distance = 3.53 Å.

[13] The aggregation of arc-shaped units could potentially lead to either a closed cyclic array or an infinite undulating tape structure (see ref. [11]). The ability of the cyclic array to encapsulate the anions may provide a driving force for its formation. Anion encapsulation in the formation of circular helicates is believed to be important (see ref. [5]).

A Dendritic Structure Containing a Designed Cleft which Controls Ligand Coordination Behavior in an Analogous Way to Proteins**

Michael J. Hannon,* Paul C. Mayers, and
Paul C. Taylor*

Nature uses metal – ion coordination complexes to undertake many tasks. Frequently it imparts function by modifying the conventional behavior of a metal complex by incorporation within a protein superstructure.[1] For example, by isolating heme groups in the center of globular proteins oxidative dimerization is prevented and *reversible* oxygen binding is achieved. Steric isolation owes much to the dimensions of such globular proteins which are much larger than the small molecules prepared by synthetic chemists. Dendrimers represent a class of monodisperse synthetic macromolecules[2] which approach the dimensions of proteins and have been proposed as potential protein and enzyme mimics.[3] For example, porphyrins have been encapsulated at the center of spherical organic dendrimers to create compounds analogous to globular electron-transfer proteins[4] and then used as oxidation catalysts.[5]

However, in nature, coordination sites are often not completely encapsulated in the core of a protein. For example, in carbonic anhydrase (CA) the N_3 zinc(II)-coordination site is situated at the foot of a cleft accessible to the solvent. The essentially hydrophobic protein cleft plays an important role in the catalytic cycle, by binding the substrate, creating a hydrogen-bonded solvent network to facilitate proton transfer, and expelling the hydrophilic product.[6] Equally importantly this cleft modifies and controls the chemistry of the coordination site. Investigations of zinc(II) species with tripodal N_3 ligands (L) reveal a strong tendency to form $[ZnL_2]^{2+}$ complexes or hydroxy-bridged dimers.[7, 8] In the enzyme the protein cavity sterically prevents the formation of these species and discrete mononuclear 1:1 complexes $[ZnL(OH)]^{+}$ and $[ZnL(OH_2)]^{2+}$ result. We were interested to see if we could imitate this natural approach to modify and control the behavior of a transition metal complex. Rather than simply isolating a complex within a globular dendritic structure we have focused on the design of systems in which a dendritic unit could be used to generate a cavity around a metal complex.

We reasoned that blocking one direction of "growth" of a dendrimer would lead to a large cleft in the structure around the site of the "blockage". If the metal binding site forms the blocking group, or is attached to it, then at high generation

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[**] This work was supported by the Leverhulme Trust. We thank the University of Warwick National 9.4T FT-ICR Mass Spectrometry Facility (EPSRC/BBSRC) for recording the FT-ICR mass spectra and the EPSRC National Mass Spectrometry Centre, Swansea, for recording other mass spectra.

this site should be surrounded by a dendrimer cleft (see Figure 1). While conventional dendrimers are considered to be spherical at higher generations with small cavities in the bulk of the molecule,[9] the dendrimers described herein are different: the cleft is quite distinct from the smaller conventional dendrimer cavities and should persist even when the dendrimer bulk becomes more densely packed.

To investigate this idea we have designed a series of dendritic ligands (Figure 1) containing a tripodal N_3 ligand (extending the CA analogy),[10] and report herein the effect of the dendrimer on the complexation ability of the tripodal ligand.

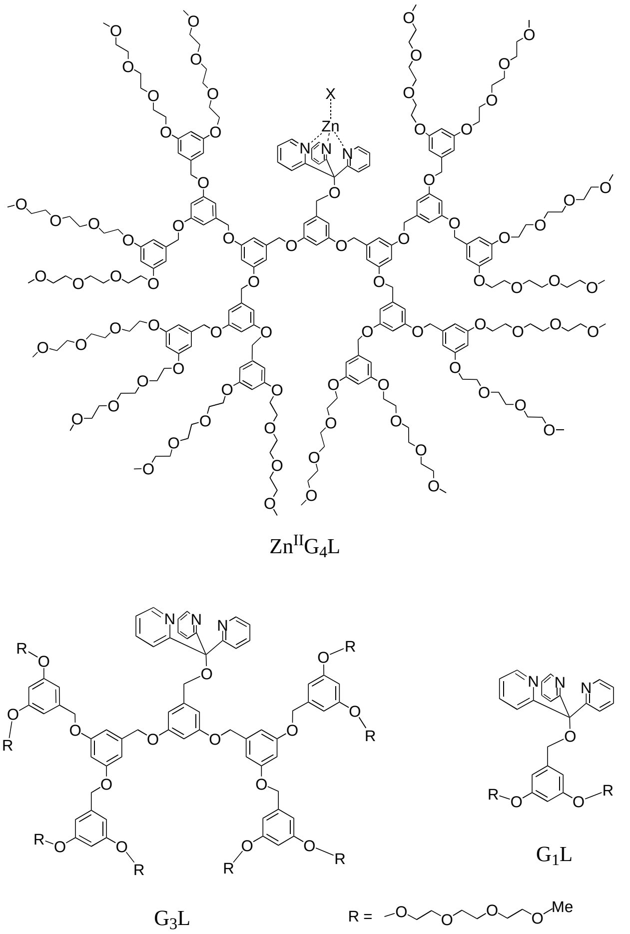
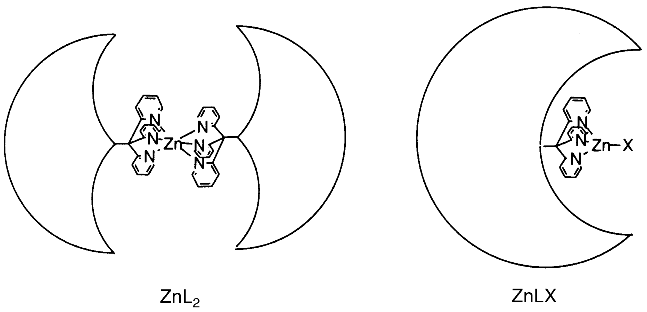


Figure 1. The N_3 binding site blocks the growth of the dendrimer as seen in the first and third generation ligands G_1L and G_3L; the reulting cleft is seen in the fourth generation complex $Zn^{II}G_4L$.

The dendrimers were prepared[10] by a Fréchet-type[11] convergent synthesis.[12] The terminal polyether groups confer excellent solubility in a wide-range of solvents.[10, 13] The zinc(II) complexes were prepared by treatment of a methanolic solution of the ligand with aqueous $ZnCl_2$. With a zinc(II) center the dendritic tripyridylmethanol unit (L) could form either an octahedral bis(L) complex $[ZnL_2]^{2+}$ or a distorted tetrahedral mono(L) complex $[ZnLX]^{n+}$ (where X is another ligand, e.g. Cl). If the dendritic structure does indeed form the desired cavity then at higher generation, as the dendrimer ligand (L) becomes larger, it should sterically prevent $[ZnL_2]^{2+}$ formation and thereby favor the $[ZnLX]^{n+}$ structure (as observed in the natural CA system).



Electrospray mass spectrometry has proved to be a powerful technique for analysis such dendrimer complexes and indicates that $[ZnLX]^{n+}$ formation is indeed the case in solution (Figure 2).[14] The mass spectra of the Zn^{II} complexes of the dendrimer ligands are dependent on the size of the dendrimer unit. Thus the mass spectrum of the $Zn^{II}G_1L$ complex (not shown) is dominated by an intense signal corresponding to $[ZnL_2]^{2+}$. At generation three, the mass spectrum of the $Zn^{II}G_3L$ complex exhibits an intense signal at m/z 1176 corresponding to $[ZnL]^{2+}$ but a more complex set of weak signals at m/z 2288, 2319, and 2387 corresponding to $[LH]^+$, $[ZnL_2]^{2+}$, and $[ZnLCl]^+$, respectively, seem to indicate that the product is a mixture of 2:1 and 1:1 ligand/metal complexes (Figure 2a). Significantly different results are obtained for G_4L (Figure 2b). The positive electrospray ionization Fourier transform ion cyclotron resonance (ES$^+$ FT-ICR) mass spectrum of the $Zn^{II}G_4L$ complex exhibits signals at m/z 2249 $[ZnL]^{2+}$, 2267 $[ZnLClH]^{2+}$, 2279 $[ZnLClNa]^{2+}$, and 2287 $[ZnLClK]^{2+}$. No signals corresponding to $[ZnL_2]^{2+}$ species were observed. The isotopic distribution of the signals matches the theoretical calculation in all four cases.

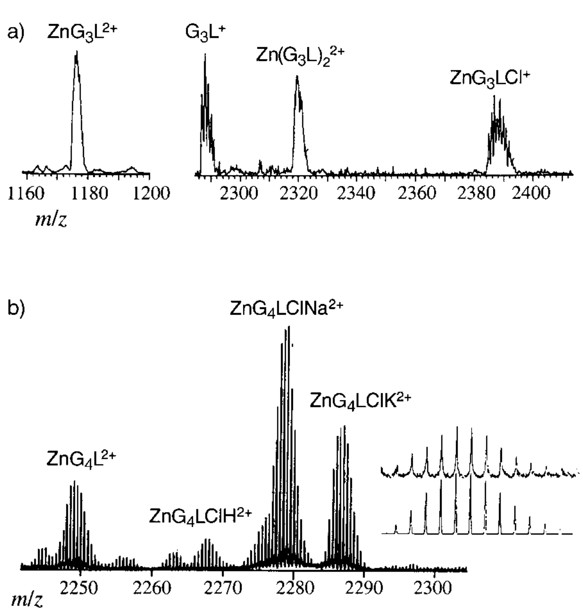


Figure 2. a) ES$^+$ mass spectrum of the $Zn^{II}G_3L$ complex; b) ES$^+$ FT-ICR mass spectrum of $Zn^{II}G_4L$ complex and (inset) an expansion of the $[ZnLClH]^{2+}$ signal together with the theoretical isotope pattern (below).

While this result does indicate that, as desired, the bulk of the dendrimer disfavors the formation of ZnL_2 species, the absence of the peak in the mass spectrum is not of itself definitive evidence. The required evidence comes from NMR spectroscopy titration studies.[15] For the generation one ligand (G_1L) in dichloromethane solution (with 5% methanol),[16] at a metal:ligand ratio of 1:2 only $[ZnL_2]^{2+}$ is detected. As the ratio of metal is increased to 1:1, resonance signals corresponding to $[ZnLX]^+$ start to appear but $[ZnL_2]^{2+}$ remains as a major species in solution.[17] Even at a ratio of 10:1 resonance signals corresponding to the $[ZnL_2]^{2+}$ species remain. Almost identical behavior is observed for both the generation two and generation three ligands (G_2L and G_3L). This is illustrated for G_3L in Figure 3a. For the generation four ligand (G_4L; Figure 3b) at a Zn:L ratio of 1:2, $[ZnL_2]^{2+}$ is still the dominant species, however, at a ratio of 1:1 only very trace amounts of $[ZnL_2]^{2+}$ are observed and the solution contains predominantly $[ZnLX]^+$. Equally dramatic effects are also observed in both CD_3OD and D_2O solutions, where for G_4L the $[ZnL_2]^{2+}$ complex is so disfavored that at a Zn:L ratio of 1:2, $[ZnLX]^+$ is the dominant species with free L and $[ZnL_2]^{2+}$ also present in the solution mixture. These NMR titrations in all three solvents reveal a quite dramatic change of behavior between generation three and generation four.

In conclusion evidence from NMR spectroscopy and ES-MS spectrometry confirm that dendritic units can be used to control and modify the conventional behavior of a complex in a similar way to that achieved by protein structures in nature. The generation four dendritic ligand ($L = G_4L$) is effective in sterically isolating a coordinated metal ion and thus disfavors the formation of ZnL_2 species and leads to the formation of 1:1 complexes. The ligand also confers excellent solubility in a wide-range of solvents, including water. An attractive feature of this dendrimer-based approach is the potential both for systematically varying the nature and composition of the cleft and for extension to the isolation of different coordination environments as observed in a wide-range of enzymes.

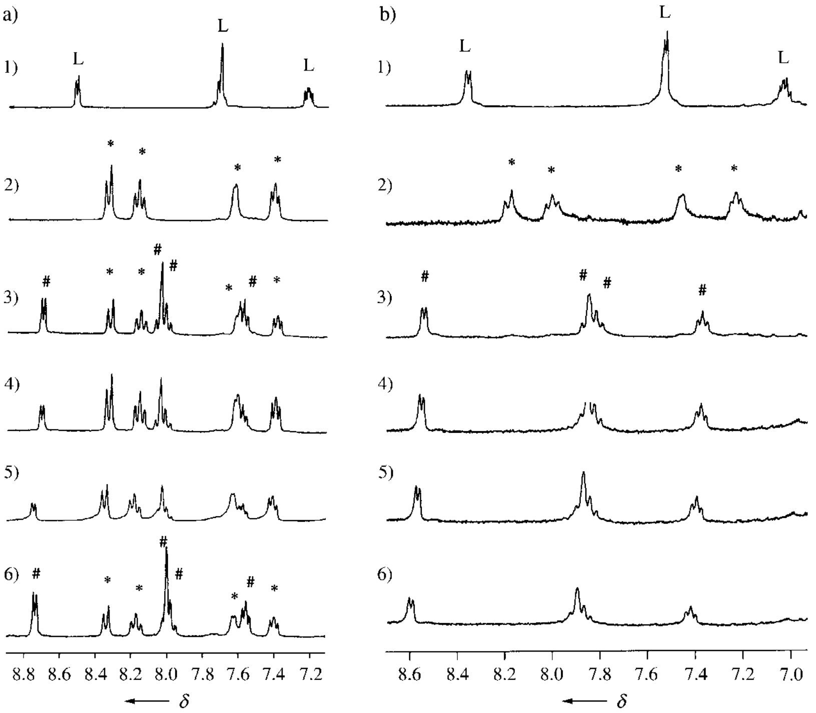


Figure 3. Pyridyl resonances in the ^1H NMR titration spectra of a) G_3L and b) G_4L with $Zn(ClO_4)_2$ in CD_3OD solution. 1) free ligand; 2) 0.5 equivalents of Zn^{II}; 3) 1 equivalent of Zn^{II}; 4) 2 equivalents of Zn^{II}; 5) 5 equivalents Zn^{II}; 6) 10 equivalents Zn^{II}. For clarity only the pyridyl resonances are shown; L = signals corresponding to the free ligand, * = signals corresponding to the 2:1 complex $[ZnL_2]^{2+}$, and # = signals corresponding to the 1:1 complex $[ZnLX]^+$.

Experimental Section

The dendritic ligands G_1L-G_4L were prepared as described in ref. [10] Electrospray mass spectra were performed on solutions of metal complexes prepared by adding excess dendrimer to the required metal salt ($ZnCl_2$). Proton NMR spectroscopy titrations were performed at constant ligand concentration, varying the metal salt concentration. $Zn(ClO_4)_2$ was used for the titrations in CD_2Cl_2 solution and $ZnCl_2$ in CD_3OD and D_2O.

Received: November 21, 2000 [Z16146]

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[1] See for example: S. J. Lippard, J. M. Berg, *Principles of Bioinorganic Chemistry*, University Science Books, Mill Valley, CA, **1994**.

[2] G. R. Newkome, C. Moorefield, F. Vögtle, *Dendritic Molecules*, VCH, Weinheim, **1996**; D. M. Haddleton, H. S. Sahota, P. C. Taylor, S. G. Yeates, *J. Chem. Soc. Perkin Trans. 1* **1996**, 649–656.

[3] J. Issberner, R. Moors, F. Vögtle, *Angew. Chem.* **1994**, *106*, 2507–2514; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2413–2420; H. F. Chow, T. K. K. Mong, M. F. Nongrum, C. W. Wan, *Tetrahedron* **1998**, *54*, 8543–8660.

[4] P. J. Dandliker, F. Diederich, A. Zingg, J.-P. Gisselbrecht, M. Gross, A. Louati, E. Sanford, *Helv. Chim. Acta* **1997**, *80*, 1773–1807.

[5] P. Bhyrappa, J. K. Yound, J. S. Moore, K. S. Suslick, *J. Am. Chem. Soc.* **1996**, *118*, 5708–5711.

[6] I. Bertini, C. Luchinat, S. Mangani, R. Pierattelli, *Comments Inorg. Chem.* **1995**, *17*, 1–15.

[7] H. Slebocka-Tilk, J. L. Cocho, Z. Frakman, R. S. Brown, *J. Am. Chem. Soc.* **1984**, *106*, 2421–2431; M. Ruf, K. Weis, H. Vahrenkamp, *J. Chem. Soc. Chem. Commun.* **1994**, 135–136; C. Kimblin, W. E. Allen, G. Parkin, *J. Chem. Soc. Chem. Commun.* **1995**, 1813–1815; G. Parkin, *Chem. Commun.* **2000**, 1971–1985.

[8] Attempts to design complexes which model both the enzyme active site and the cavity have been reported; Walton has pioneered an elegant approach creating cavities from aryl arms attached about a trisimine coordination site and several groups have attached metal complexes beneath a cyclodextrin or calixarene cavity: B. Greener, M. H. Moore, P. H. Walton, *Chem. Commun.* **1996**, 27–28; L. Cronin, B. Greener, M. H. Moore, P. H. Walton, *J. Chem. Soc. Dalton Trans.* **1996**, 3337–3339; C. C. Tang, D. Davalian, P. Huang, R. Breslow, *J. Am. Chem. Soc.* **1978**, *100*, 3918–3922; I. Tabushi, *Acc. Chem. Res.* **1982**, *15*, 66–72; S. Blanchard, L. Le Clainche, M.-N. Rager, B. Chansou, J.-P. Tuchagues, A. F. Duprat, Y. Le Mest, O. Reinaud, *Angew. Chem.* **1998**, *110*, 2681–2684; *Angew. Chem. Int. Ed.* **1998**, *37*, 2732–2735.

[9] Binding of guests inside conventional dendrimer cavities has been reported, for example, J. F. G. A. Jansen, E. M. M. de Brabander-van den Berg, E. W. Meijer, *Science* **1994**, *266*, 1226–1229.

[10] Synthetic strategies, preparative details, and characterization data for the metal-free dendritic ligands: M. J. Hannon, P. C. Mayers, P. C. Taylor, *J. Chem. Soc. Perkin Trans. 1* **2000**, 1881–1889; M. J. Hannon, P. C. Mayers, P. C. Taylor, *Tetrahedron Lett.* **1998**, 8509–8512.

[11] C. J. Hawker, J. M. J. Fréchet, *J. Am. Chem. Soc.* **1990**, *112*, 7638–7647.

[12] Kaifer and co-workers have reported dendritic structures in which a ferrocene or dansyl group is located "off-center" within Newkome-type aliphatic amide dendrimers through which they anticipate inducing directional properties. C. M. Cardona, T. D. McCarley, A. E. Kaifer, *J. Org. Chem.* **2000**, *65*, 1857–1864; C. M. Cardona, J. Avarez, A. E. Kaifer, T. D. McCarley, S. Pandey, G. A. Baker, N. J. Banzangi, F. V. Bright, *J. Am. Chem. Soc.* **2000**, *122*, 6139–6144.

[13] D. K. Smith, F. Diederich, *Chem. Commun.* **1998**, 2501–2502; D. J. Pesak, J. S. Moore, T. E. Wheat, *Macromolecules* **1997**, *30*, 6467–6482.

[14] Solutions of metal complexes for ESI-MS were prepared by adding excess dendrimer to the required metal salt.

[15] The large shift in the pyridyl signals in the ^{1}H NMR spectrum upon addition of zinc(II) salts to CD_3OD, CD_2Cl_2, and D_2O solutions of the dendritic ligands suggests that the metal ion binds to the tripodal nitrogen-donor core and does not interact with the oxygen-donor atoms of the polyether chain.

[16] The titrations were undertaken in 95% CD_2Cl_2/5% CD_3OD since the zinc(II) perchlorate salt is not soluble in neat CD_2Cl_2.

[17] The chemical shifts of the protons on trispyridyl ligands are quite different in $[ML]^{n+}$ and $[ML_2]^{n+}$ environments, with H6 being most affected; see, for example: R. T. Jonas, T. D. P. Stack, *Inorg. Chem.* **1998**, *37*, 6615–6629, and refs therein.

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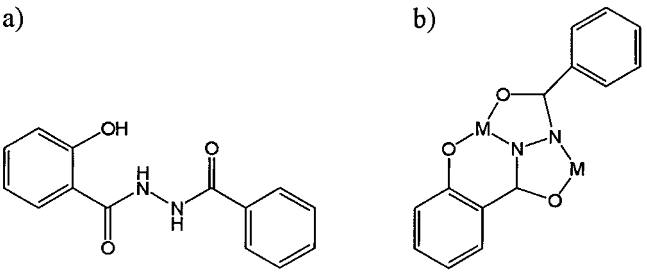
[30]Metallacrown-10 Compounds: $[Mn(C_{14}H_9N_2O_3)(CH_3OH)]_{10}\cdot 5\,CH_2Cl_2\cdot 16\,CH_3OH\cdot H_2O$ and $[Fe(C_{14}H_9N_2O_3)(CH_3OH)]_{10}\cdot 3\,CH_2Cl_2\cdot 12.5\,CH_3OH\cdot 5\,H_2O$**

Shi-Xiong Liu,* Shen Lin, Bi-Zhou Lin, Chi-Chang Lin, and Jian-Quan Huang

Metallacrowns are a new class of multinuclear clusters that are analogous to crown ethers in both structure and function.[1, 2] One may substitute heteroatoms such as transition metals and nitrogen atoms for the methylene carbon atoms of the parent crown ether complexes to form metallacrowns. Therefore, there has been considerable interest in metallacrown chemistry owing to its potential applications in chemically modified electrodes, anion-selective separation agents, liquid-crystal precursors, and magnetic materials.[3] Salicylhydroxamic acid (H_3shi) was used as the template ligand in the synthesis of the early metallacrowns. Many examples of this kind of metallacrown are known, for example, [9]metallacrowns-3,[3, 4] [12]metallacrowns-4,[1, 2, 5–8] and [15]metallacrowns-5,[9] which have a $[M\text{-}N\text{-}O]_n$ repeat unit that forms a cyclic structure. Several compounds with the metallacrown structure type have been developed.[10] Recently, an [18]metallacrown-6 using *N*-formylsalicylhydrazide (H_3fshz) as a ligand was reported.[11] This metallacrown is the second kind of metallacrown with a $[M\text{-}N\text{-}N]_n$ repeating unit in which nitrogen atoms replace all the oxygen atoms in the cyclic structure.

Although some [9]metallacrowns-3, [12]metallacrowns-4, [15]metallacrowns-5, and an [18]metallacrown-6 are known, there has yet been no report of any [30]metallacrown-10. Taking the limitations of metallacrowns based solely on shi^{3-} and fshz^{3-} templates into account, we have greatly expanded the types of precursor ligands with the intention of modifying the ring size, as well as the electronic, magnetic, and other physical properties of the metallacrowns. We found that the choice of ligand plays an important role in preparing new metallacrowns with high nuclear number, such as the title [30]metallacrowns-10. Herein we provide a new potential pentadentate ligand *N*-phenylsalicylhydrazidate (**1**) (H_3bzshz, Scheme 1 a) and the first two [30]metallacrowns-10, **2** and **3**.



Scheme 1. Ligand H_3bzshz (a) and basic biding sites in compounds **2** and **3** (M = Mn, Fe) (b).

The two title [30]metallacrowns-10 are also the second kind of metallacrown with a $[M{-}N{-}N]_n$ repeating unit, which may be more appropriately called an azametallacrown.[12]

$[Mn(C_{14}H_9N_2O_3)(CH_3OH)]_{10}\cdot 5\,CH_2Cl_2\cdot 16\,CH_3OH\cdot H_2O$ **2**

$[Fe(C_{14}H_9N_2O_3)(CH_3OH)]_{10}\cdot 3\,CH_2Cl_2\cdot 12.5\,CH_3OH\cdot 5\,H_2O$ **3**

Single-crystal X-ray analysis of compound **2** (Figure 1) showed that there is a planar decanuclear 30-membered ring in the manganese metallacrown core. The 30-membered core ring exhibits crystallographic centrosymmetry and is a $[Mn\text{-}N\text{-}N]_{10}$ ring with neighboring Mn···Mn interatomic distances of 4.906(1)–4.986(2) Å. The size of the cavity in the 30-membered ring, measured between the opposite carbon atoms (less 1.57 Å for the van der Waals radii of carbon) is 6.80, 7.61, 6.39, 7.48, and 7.23 for C(13)–C(13a), C(26)–

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[**] We are grateful for financial support from the National Natural Science Foundation of China (No. 29771007) and the Natural Science Foundation of Fujian Province, China.