

# Hexameric C-alkylpyrogallol[4]arene molecular capsules sustained by metal-ion coordination and hydrogen bonds

Robert M. McKinlay, Praveen K. Thallapally and Jerry L. Atwood\*

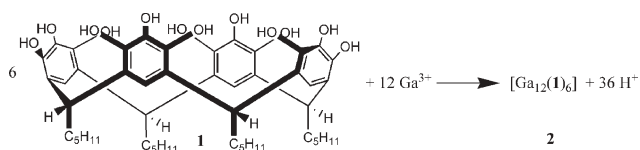
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Large multicomponent nanospheroid arrays consisting of six C-pentylpyrogallol[4]arene molecules and 12 Ga<sup>3+</sup> metal-ions which in turn enclose 1150 Å<sup>3</sup> of chemical space are reported.

Inspired by architectural beauty and aesthetic appeal, the synthesis of host nanospheroid structures is becoming increasingly feasible and remains an area of continuing fascination.<sup>1</sup> Such nanospheroid structures generally conform to the shapes described by the Platonic or Archimedean solids.<sup>2</sup> In addition, these nanospheroid architectures continue to attract great interest and focus as a result of potential guest encapsulation.<sup>3</sup> In this context, chemists have used small cyclic concave-shaped molecules such as: the C-methylresorcin[4]arene;<sup>4</sup> the C-alkylpyrogallol[4]arenes;<sup>5</sup> the calix[4]arenes;<sup>6</sup> and cavitand molecules<sup>7</sup> to assemble nanometre-sized molecular capsules. Both the covalent and non-covalent approach have been successful in this endeavor. For example, a hexameric cavitand nanospheroid structure was recently assembled by means of reversible covalent imine interactions.<sup>7</sup> On the other hand, six molecules of C-methylresorcin[4]arene and eight water molecules self-assemble into a chiral snub cube structure stabilized by 60 hydrogen bond interactions.<sup>4a</sup> In addition, six molecules of the closely related C-alkylpyrogallol[4]arene self-assemble into achiral octahedral structures stabilized by 72 hydrogen bond interactions.<sup>8</sup>



From a pictorial point of view, hydrogen bonding interactions between the hydroxy groups on the seams of these C-alkylpyrogallol[4]arene hexameric assemblies can be substituted for metal-ion coordination interactions without disruption to the overall hexameric structure. Indeed, we previously reported the formation of an octahedral molecular capsule assembled from 6 C-alkylpyrogallol[4]arene molecules and 24 Cu<sup>2+</sup> metal-ions.<sup>9</sup> This metal-coordinated assembly was structurally identical to its hydrogen bonded cousin even though 24 Cu<sup>2+</sup> ions replaced 48 hydrogen atoms at the seams of the hexamer.

There are few examples of metal–ligand coordination combined with hydrogen bonding interactions which hold large multicomponent molecular assemblies together, although there are numerous examples of metal–ligand only assemblies.<sup>10</sup> We herein

report the one-step formation of a 22 component molecular nanospheroid assembly **2** stabilized by metal-ion coordination and hydrogen bonding interactions (Fig. 1). Addition of two equivalents of aqueous Ga(NO<sub>3</sub>)<sub>3</sub> to a solution of C-pentylpyrogallol[4]arene **1** in acetone (**2a**) or acetonitrile (**2b**) yielded crystals suitable for X-ray diffraction studies.† The nanospheroid array **2a** (from acetone) consists of six molecules of C-pentylpyrogallol[4]arene, 12 Ga<sup>3+</sup> metal-ions, and 4 water molecules located at the seams of the nanospheroid. The calixarenes are arranged at the vertexes of a squeezed octahedron which in turn generates a molecular cavity volume of approximately 1150 Å<sup>3</sup>.<sup>11b</sup> The dimensions between opposite calixarene centroids within **2a** are approximately 13 × 16 × 16 Å.

As mentioned previously, six C-alkylpyrogallol[4]arene self-assemble into octahedral nanospheroids stabilized by 72 hydrogen

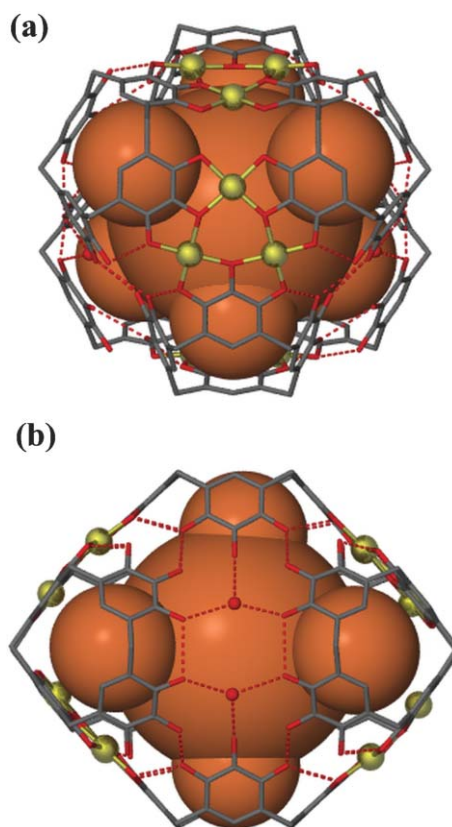
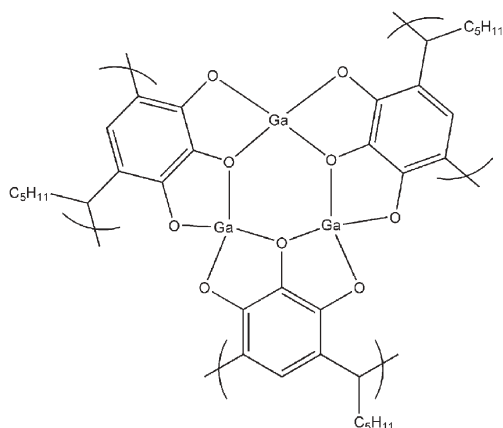


Fig. 1 Different views of structure **2a**. Ga<sup>3+</sup> ions colored gold, water molecules at the seams colored red and the potential cavity void space colored orange. The alkyl groups; guest molecules; metal-coordinated water molecules; and hydrogen atoms have been removed for clarity.

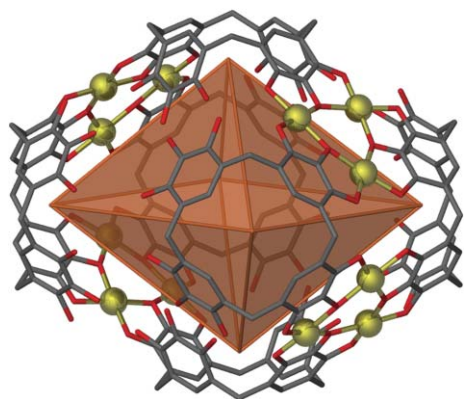
Department of Chemistry, University of Missouri-Columbia, Columbia, MO 65211, USA. E-mail: AtwoodJ@missouri.edu; Fax: +1 573 882 2754



**Fig. 2** One of the four  $[\text{Ga}_3(\mu_3\text{-O})_3(\text{O})_6]$  units that hold **2a** together. Axial metal-coordinated water molecules removed for clarity.

bonding interactions, of which 24 are intramolecular. However, the addition of 12  $\text{Ga}^{3+}$  metal-ions on the seams of the hexameric array results in the loss of 36 protons and therefore 36 hydroxy groups remain to participate in various hydrogen bonding interactions. The nanospheroid **2a** is held together by 4 six-membered slightly curved  $[\text{Ga}_3(\mu_3\text{-O})_3(\text{O})_6]$  units (Fig. 2). An alternative viewing of **2a** is that half the octahedral faces are capped by  $[\text{Ga}_3(\mu_3\text{-O})_3(\text{O})_6]$  units (Fig. 3). The  $\text{Ga}^{3+}$  equatorial positions are occupied by deprotonated hydroxy groups from the calixarene subunits whereas the axial positions are occupied by water molecules, 12 of which point inward toward the cavity center. Four of the calixarene subunits of **2a** have metal-ions located at their 1,2 pyrogallol sites ( $C_1$ ), whereas the remaining two calixarenes have metal-ions positioned at their 1,4 sites ( $C_{2v}$ ).

A detailed inspection of **2a** revealed the assembly is held together by 20 intramolecular hydrogen bonding interactions, 4  $\text{O-H}\cdots\text{O-H}$  interactions, and 16 interactions of the type  $\text{O-H}\cdots\text{O}^-$ . Although hydrogen atoms were not located, hydrogen bonds are implied by the short  $\text{O}\cdots\text{O}$  contacts. The nanospheroid **2a** is stabilized by hydrogen bonding interactions between the hydroxy groups on the upper rim of the calixarene subunits and 4 water molecules located at the seams of **2a** (Fig. 1b). Although the atomic positions of the guest molecules within **2a** are vague and highly disordered, the thermal parameters and positions of the 4



**Fig. 3** Structure of **2a** showing its octahedral faces capped with four  $[\text{Ga}_3(\mu_3\text{-O})_3(\text{O})_6]$  units.

water molecules were well-behaved. The hydrogen bonding pattern suggests that each of the 4 water molecules contribute three intermolecular hydrogen bonds along the surface of **2a** which seals up potential surface voids ( $\text{O}\cdots\text{O} = 2.682\text{--}2.979 \text{ \AA}$ ;  $\text{O}\cdots\text{O}\cdots\text{O} = 114.10\text{--}124.48^\circ$ ). This leads to a total of 12 intermolecular hydrogen bonding interactions between the calixarenes and 4 water molecules. However, the remaining hydrogen bonding pattern suggests there are a total of 10 direct intermolecular hydrogen bonding interactions ( $\text{O-H}\cdots\text{O-H}$ ) between hydroxy groups from the calixarenes (Fig. 1b).

The  $^1\text{H}$  NMR spectra of **2a** in  $\text{CD}_3\text{CN}$  shows the  $\text{CH}$  hydrogen atoms of the bridging methines exhibit four broad multiplet peaks at 4.27, 4.32, 4.37 and 4.42 ppm respectively. The aromatic hydrogen atoms are also split into numerous singlets at 6.80, 6.85, 6.95, 6.98 and 7.05 ppm. These splittings are consistent with the calixarenes being distorted from perfect  $C_{4v}$  symmetry ( $C_{4v}$  usually found in the hydrogen bonding hexamer assemblies and 2D sheet-like structures). The  $^1\text{H}$  NMR spectra of **2a** crystals also suggested there are a minimum of 6 acetone molecules within the cavity. The integral peak at 2.24 ppm corresponds to 6.24 acetone molecules per hexamer, although this peak overlaps with adjacent broad peaks corresponding to surface acetone and water. Therefore this integral is subject to inaccuracy. However, based upon previous examples,<sup>8</sup> one solvent molecule usually resides at the concave base of each calixarene subunit with the remaining space occupied with solvent and/or water molecules. The downfield shift of the encapsulated acetone molecules is consistent with sufficient hydrogen bonding with metal-coordinated water molecules. Indeed, it was previously shown that within the assembly  $[\text{Ga}_{12}(\text{C-propylpyrogallol-}[4]\text{arene})_6]$ , metal-coordinated water molecules form hydrogen bonding interactions with guest molecules.<sup>12</sup>

Addition of two equivalents of aqueous  $\text{Ga}(\text{NO}_3)_3$  to a solution of  $\text{C-pentylpyrogallol}[4]\text{arene}$  **1** in acetonitrile yielded crystals suitable for X-ray diffraction studies. The nanospheroid array **2b** was determined to be structurally similar to **2a**. Six molecules of  $\text{C-pentylpyrogallol}[4]\text{arene}$ , 12  $\text{Ga}^{3+}$  metal-ions, and 4 water molecules at the seams of the nanospheroid enclose  $1150 \text{ \AA}^3$  of space.<sup>11</sup> The  $\text{Ga}^{3+}$  metal-ions were located at the same sites as in structure **2a**. Although, X-ray analysis could not determine the guest molecules, the  $^1\text{H}$  NMR spectra of crystals **2b** in  $D_6$ -acetone suggested there were 6 to 7 acetonitrile molecules encapsulated with **2b**. Indeed, it was previously shown that a hydrogen bonded hexamer contained 10 acetonitrile molecules per cavity.<sup>5c</sup> However, in our case, the 12 metal-coordinated water molecules within the cavity, combined with the squeezed octahedral structure reduced the cavity volume to approximately  $950 \text{ \AA}^3$ .<sup>11c</sup>

In conclusion, metal-ion coordination can replace hydrogen bonding interactions at the seams of  $\text{C-alkylpyrogallol}[4]\text{arene}$  hexameric structures. Also these large multicomponent nanospheroid assemblies are held together by a combination of metal-ion coordination and hydrogen bonding interactions.

## Notes and references

† Compound **1** (0.1 mmol) and  $\text{Ga}(\text{NO}_3)_3\cdot\text{H}_2\text{O}$  (0.2 mmol) were dissolved in water (1 ml) and acetone (5 ml). Yield 42%. Crystal data for **2a**:  $\text{C}_{341.33}\text{H}_{403.33}\text{Ga}_{12}\text{O}_{137}$ ,  $M = 7534.57$ , colorless block,  $0.40 \times 0.35 \times 0.20 \text{ mm}^3$ , monoclinic, space group  $P2_1/n$  (No. 14),  $a = 26.332(5)$ ,  $b = 28.646(5)$ ,  $c = 29.686(5) \text{ \AA}$ ,  $\beta = 104.993(3)^\circ$ ,  $V = 21630(7) \text{ \AA}^3$ ,  $Z = 2$ ,  $D_c = 1.157 \text{ g cm}^{-3}$ ,  $F_{000} = 7839$ ,  $\text{MoK}\alpha$  radiation,  $\lambda = 0.71073 \text{ \AA}$ ,  $T = 173(2) \text{ K}$ ,  $2\theta_{\text{max}} = 54.3^\circ$ , 150599 reflections collected, 47676 unique ( $R_{\text{int}} = 0.0701$ ).

Final GooF = 1.445,  $R_1 = 0.1195$ ,  $wR_2 = 0.3365$ ,  $R$  indices based on 27759 reflections with  $I > 2\sigma(I)$  (refinement on  $F^2$ ), 2311 parameters, 572 restraints. Lp and absorption corrections applied,  $\mu = 0.812 \text{ mm}^{-1}$ . All non-hydrogen atoms were refined anisotropically.

The acetone solution used to crystallize **2a** was removed and **2a** was dried over filter paper for 5 min.  $^1\text{H NMR}$  (500 MHz,  $\text{CD}_3\text{CN}$ , 300.0 K):  $\delta = 0.94$  (m, 72H,  $-\text{CH}_3$ ); 1.45 (m, 144H,  $\beta\text{-CH}_2$ ,  $\gamma\text{-CH}_2$ ,  $\delta\text{-CH}_2$ ); 2.24 (s,  $\sim 37.49\text{H}$ , encapsulated acetone); 2.42 (m, 48H,  $\alpha\text{-CH}_2$ ); 4.27, 4.32, 4.37, 4.42, (m, 24H,  $-\text{CH}$ ); 6.80, 6.85, 6.91, 6.95, 6.98, 7.05 (s, 24H, Ar). OH peaks were not located.

Compound **1** (0.1 mmol) and  $\text{Ga}(\text{NO}_3)_3 \cdot \text{H}_2\text{O}$  (0.2 mmol) were dissolved in water (0.5 ml) and acetonitrile (5 ml). Yield 38%. Crystal data for **2b**:  $\text{C}_{300}\text{H}_{292}\text{Ga}_{12}\text{N}_8\text{O}_{119}$ ,  $M = 6750.06$ , colorless plate,  $0.15 \times 0.1 \times 0.05 \text{ mm}^3$ , monoclinic, space group  $C2/c$  (No. 15),  $a = 41.443(4)$ ,  $b = 29.295(3)$ ,  $c = 36.851(4) \text{ \AA}$ ,  $\beta = 112.666(2)^\circ$ ,  $V = 41285(7) \text{ \AA}^3$ ,  $Z = 4$ ,  $D_c = 1.086 \text{ g cm}^{-3}$ ,  $F_{000} = 13888$ , MoK $\alpha$  radiation,  $\lambda = 0.71073 \text{ \AA}$ ,  $T = 173(2) \text{ K}$ ,  $2\theta_{\text{max}} = 46.6^\circ$ , 108094 reflections collected, 29749 unique ( $R_{\text{int}} = 0.2496$ ). Final GooF = 1.180,  $R_1 = 0.1324$ ,  $wR_2 = 0.3445$ ,  $R$  indices based on 9358 reflections with  $I > 2\sigma(I)$  (refinement on  $F^2$ ), 2059 parameters, 512 restraints. Lp and absorption corrections applied,  $\mu = 0.842 \text{ mm}^{-1}$ . All non-hydrogen atoms of **2b** were refined anisotropically.

The acetonitrile solution used to crystallize **2b** was removed and crystals of **2b** were dried over filter paper for 5 min.  $^1\text{H NMR}$  (500 MHz,  $D_6$ -acetone, 300.0 K):  $\delta = 0.94$  (m, 72H,  $-\text{CH}_3$ ); 1.45 (m, 144H,  $\beta\text{-CH}_2$ ,  $\gamma\text{-CH}_2$ ,  $\delta\text{-CH}_2$ ); 2.27 (s,  $\sim 20.39\text{H}$ , encapsulated acetonitrile); 2.38 (m, 48H,  $\alpha\text{-CH}_2$ ); 4.23, 4.39, (m, 24H,  $-\text{CH}$ ); 6.84, 6.91, 7.03, 7.36, 8.61 (m, 60H, Ar and OH peaks).  $\text{D}_2\text{O}$  exchange of **2b** showed the peaks from 6.84 to 8.61 ppm are reduced to 5 peaks corresponding to  $\sim 27$  aromatic hydrogen atoms;  $^1\text{H NMR}$  of **2b** from the selected range 6 to 9 ppm (500 MHz,  $D_6$ -acetone + 2 drops  $\text{D}_2\text{O}$ , 300.0 K): 6.72 (s, 4H), 6.89 (s, 4H), 6.95 (s, 8H), 7.03 (s, 8H), 7.36 (s, 3H).

Structures were solved and refined using the SHELX-97 programs<sup>13</sup> and X-Seed.<sup>14</sup> The figures were prepared using X-Seed, POV-Ray.<sup>15</sup> CCDC 604426 and 604427. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b605204e

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