Stabilization of a Reactive Cationic Species by Supramolecular Encapsulation**

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In the study of molecular capsules, the stabilization of reactive species and reactions of encapsulated guests are areas of great interest as possible methods for drug delivery and for use as molecular reaction vessels.[1–4] Organic capsule molecules such as hemicarcerands are covalently linked cages with large internal cavities and wide pores for the incorporation of guest species. These molecular capsules have been found to stabilize cyclobutadiene,[5] *o*-benzyne,[6] 1,2,4,6-cycloheptatetraene,[7] and dibenzoyl peroxide[8] as encapsulated guests, and sulfenic and selenic acids through covalent linkage to the capsule molecules.[9]

More recently, self-assembly has been used to synthesize structures held together by weaker interactions including metal coordination and hydrogen bonds.[3, 10–12] These cage complexes are also capable of selectively encapsulating guest molecules, including the encapsulation of C-shaped molecules reported by Kusukawa and Fujita,[13] and the cation inclusions reported by Raymond et al.[14] Here we report that the $[Ga_4L_6]^{12-}$ supramolecular tetrahedron[15] (Figure 1) is capable of encapsulating and stabilizing the reactive cationic species $[Me_2C(OH)PEt_3]^+$, the first trapping of such a species.

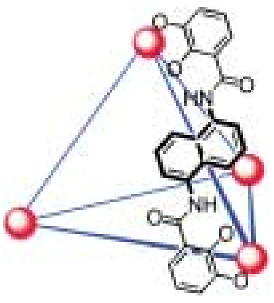


Figure 1. Schematic drawing of the $[Ga_4L_6]^{12-}$ tetrahedron showing the structure of the ligand (L); blue lines represent ligand molecules, and red circles represent gallium atoms.

The ^1H NMR spectrum recorded upon addition of PEt_3 to a solution of $Na_{12}[Ga_4L_6]$ in D_2O shows upfield-shifted resonance signals in the $\delta = -1$ to -2 range (Figure 2). Such upfield-shifted resonance signals are characteristic of encapsulated guest molecules.[10, 14] The doublet of triplets observed at $\delta = -1.12$ ($J_{H,P} = 17$, $J_{H,H} = 8$ Hz) is similar to signals seen for the methyl groups of triethylphosphine. A corresponding signal for the methylene groups of a PEt_3 moiety can be seen at $\delta = -1.56$. The presence of two doublets at $\delta = -1.42$ ($J_{H,P} = 15$ Hz) and $\delta = -1.53$ ($J_{H,P} = 15$ Hz), however, indicated that this molecule was not simply triethylphosphine. We assigned these encapsulated guest signals to the phosphine–acetone adduct, $[Me_2C(OH)PEt_3]^+$ (**1**), formed from the reaction of PEt_3 with small amounts of acetone present from the synthesis of the tetrahedral cluster. Thus, the doublets observed at $\delta = -1.42$ and $\delta = -1.53$ were assigned to the two methyl groups from the Me_2COH moiety. Diastereotopic splitting of the methyl protons in the ^1H NMR spectrum is an effect which has been previously observed for encapsulated guest molecules.[15] Integration of the observed signals support these assignments.

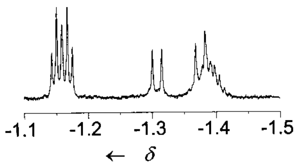
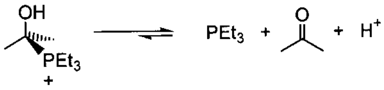


Figure 2. 500 MHz ^1H NMR spectrum of $Na_{11}[Ga_4L_6 \supset \mathbf{1}]^+$ in D_2O.

Encapsulation of this phosphorus-containing cation can be observed by ^{31}P NMR as well as ^1H NMR spectroscopy. In the $^{31}P\{^1H\}$ NMR spectrum of this mixture, several resonance signals are observed: at $\delta = 31.2$ (s), 37.1 (s), 48.5 (1:1:1 t, $J_{P,D} = 44$ Hz), 63.8 (s), and 68.3 (s). The signal at $\delta = 37.1$ is attributed to that of the encapsulated guest, while the remaining signals are due to unidentified decomposition products of PEt_3 in water.[16] The same ^1H and ^{31}P NMR signals of the tetrahedral $[Ga_4L_6]^{12-}$ cluster with its $[Me_2C(OH)PEt_3]^+$ guest were observed when this experiment was repeated in CD_3OD.

The cationic species **1** is formed by the reaction of triethylphosphine and acetone in the presence of protons. Although this species has been synthesized and isolated under anhydrous conditions,[17–19] it decomposes in aqueous solutions (due to the negligible concentration of acetone) according to the equilibrium shown in Scheme 1. Thus, observation of **1** in D_2O indicates that encapsulation inside the tetrahedral cluster stabilizes this reactive species. However, because of the low concentration of acetone in the D_2O solution, this encapsulated species decomposes as it slowly comes out of the cluster cavity. Because of its instability in low acetone concentrations, it is likely that **1** is in fact formed inside the tetrahedral cavity. ^1H NMR evidence indicates that the "empty" $[Ga_4L_6]^{12-}$ cluster actually contains acetone molecules as guests inside the tetrahedral cavity. We infer that protonated phosphine, $HPEt_3^+$, diffused into the cluster cavity and reacted with an encapsulated acetone molecule to form **1**.



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Scheme 1. Decomposition equilibrium of $[Me_2C(OH)PEt_3]^+$ (**1**) in the presence of water.

To confirm our identification of the encapsulated guest molecule, the phosphonium salt $[Me_2C(OH)PEt_3][Br]$ was independently synthesized.[20] When this phosphonium salt was added to solutions of $Na_{12}[Ga_4L_6]$ in CD_3OD,[21] ^1H NMR signals which corresponded to those observed previously upon addition of PEt_3 were seen in the ^1H NMR spectra.

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Observation of identical ^1H and ^{31}P NMR resonance siganls with addition of either PEt_3 or $[Me_2C(OH)PEt_3][Br]$ to a solution of the tetrahedral cluster is further evidence that the encapsulated species is in fact **1**.

ESI mass spectrometry has previously proven useful for characterizing multiply charged coordination compounds of this type in solution.[22–24] In this case also, mass spectrometry provided conclusive proof that **1** was encapsulated as a guest. In the electrospray mass spectrum of $Na_{11}[Ga_4L_6 \supset \mathbf{1}]$ in methanol (Figure 3a), signals for $Na_8[Ga_4L_6 \supset \mathbf{1}]^{3-}$ and $Na_7[Ga_4L_6 \supset \mathbf{1}]^{4-}$ were observed at *m/z* 1066 and *m/z* 794, respectively. Weaker signals at *m/z* 751 correspond to the empty $Na_8[Ga_4L_6]^{4-}$ cluster. The exchange of Na^+ for H^+ ions accounts for the distribution of signals seen for all species observed in this spectrum. Addition of three and six equivalents of NaOH decreased the amount of protonated species (Figure 3b and 3c). High-resolution FT mass spectra for the $Na_8[Ga_4L_6 \supset \mathbf{1}]^{3-}$ and $Na_7[Ga_4L_6 \supset \mathbf{1}]^{4-}$ species have confirmed the chemical composition of the cluster (Figure 4).[25]

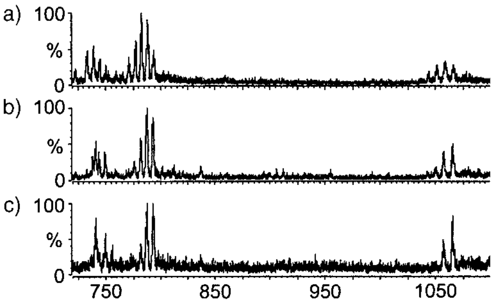

Figure 3. a) Electrospray mass spectrum of $Na_{11}[Ga_4L_6 \supset \mathbf{1}]$; b) mass spectrum after addition of three equivalents of NaOH; c) mass spectrum after addition of six equivalents of NaOH.

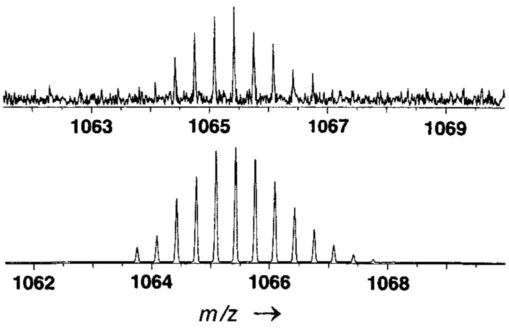

Figure 4. High-resolution mass spectrum of $Na_{11}[Ga_4L_6 \supset \mathbf{1}]^{3-}$ (top) and calculated spectrum (bottom).

Incorporation of the cationic $[Me_2C(OH)PEt_3]^+$ species instead of the neutral PEt_3 into the $Na_{12}[Ga_4L_6]$ cluster gives further proof that cationic guest molecules are preferentially encapsulated in this tetrahedral cluster as was previously observed.[14] Most remarkable, however, is the stabilization of this phosphine–acetone adduct when encapsulated as a guest. Formation of this molecule inside the tetrahedral cluster would also account for the observation of this adduct in wet methanolic and even aqueous solutions. This stabilization indicates that the guest cation **1** only slowly diffuses out of the host cavity in solution, remaining stable in D_2O for several hours, and in CD_3OD for at least one day.

In summary, the stabilization of the ion $[Me_2C(OH)PEt_3]^+$ by encapsulation in the tetrahedral cluster $Na_{12}[Ga_4L_6]$ is the first example of guest stabilization in a self-assembled supramolecular cluster. Similar to some reactions in micelles, stabilization of encapsulated guests in these nanoscale clusters could make it possible to perform reactions otherwise disfavored by dilute solution conditions.

Experimental Section

^1H and $^{31}P\{^1H\}$ NMR spectra were obtained on a DRX-500 spectrometer at 500 MHz and 122 MHz, respectively. Chemical shifts for ^1H and ^{31}P NMR spectra are reported in ppm (δ) relative to $SiMe_4$ and H_3PO_4, respectively. Triethylphosphine was purchased from Aldrich and used as received. $Na_{12}[Ga_4L_6]$[15] and $[Me_2C(OH)PEt_3][Br]$[19] were synthesized by using published procedures.

Electrospray mass spectrometry was performed on a Quattro (Micromass) triple quadrupole mass spectrometer. High-resolution mass spectral data were acquired by using a Bruker Apex II 7 Tesla actively shielded FTICR mass spectrometer equipped with an Analytica electrospray source (off axis probe). Sample solutions were 300 pmol μL^{-1} in methanol with Na^+ as counterions. Calibration was performed with NaI standard solutions.

NMR studies of $Na_{12}[Ga_4L_6 \supset \mathbf{1}]$: NMR spectra were obtained for a sample of $[Na_{11}Ga_4L_6]$ (33 mg, 11 μmol) in D_2O with added PEt_3 (4.8 μL, 32.5 μmol). ^1H NMR (500 MHz, D_2O): $\delta = 8.20$ (d, 12H; Ar_NH), 7.84 (d, 12H; Ar_NH), 7.41 (dd, 12H; Ar_CH), 7.12 (t, 12H; Ar_NH), 6.82 (dd, 12H; Ar_CH), 6.69 (t, 12H; Ar_CH), −1.12 (dt, 9H; $PCH_2\mathit{CH_3}$), −1.42 (d, 3H; CMe_2), overlapping signals at −1.53 (d, CMe_2) and −1.56 (m, $P\mathit{CH_2}CH_3$) with total integration of 9H.

Mass spectra of $Na_{11}[Ga_4L_6 \supset \mathbf{1}]$: Mass spectrometry samples were obtained by removing an aliquot (160 μL) from the NMR samples and diluting the solution to 0.5 mL with methanol. MS (ESI): *m/z*: 1065.6 ($Na_8[Ga_4L_6 \supset \mathbf{1}]^{3-}$), 1058.4 ($HNa_7[Ga_4L_6 \supset \mathbf{1}]^{3-}$), 1050.7 ($H_2Na_6[Ga_4L_6 \supset \mathbf{1}]^{3-}$), 1044.1 ($H_3Na_5[Ga_4L_6 \supset \mathbf{1}]^{3-}$), 793.6 ($Na_7[Ga_4L_6 \supset \mathbf{1}]^{4-}$), 788.1 ($HNa_6[Ga_4L_6 \supset \mathbf{1}]^{4-}$), 782.9 ($H_2Na_5[Ga_4L_6 \supset \mathbf{1}]^{4-}$), 777.3 ($H_3Na_4[Ga_4L_6 \supset \mathbf{1}]^{4-}$), 771.5 ($H_4Na_3[Ga_4L_6 \supset \mathbf{1}]^{4-}$), 750.7 ($Na_8[Ga_4L_6]^{4-}$), 745.3 ($HNa_7[Ga_4L_6]^{4-}$), 739.7 ($H_2Na_6[Ga_4L_6]^{4-}$), 733.2 ($H_3Na_5[Ga_4L_6]^{4-}$).

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Nanosized $Pd_{145}(CO)_x(PEt_3)_{30}$ Containing a Capped Three-Shell 145-Atom Metal-Core Geometry of Pseudo Icosahedral Symmetry[**]

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Dedicated to Professor Dr. Heinrich Vahrenkamp
on the occasion of his 60th birthday

Presented herein are the geometrical features of a stoichiometric capped three-shell palladium carbonyl phosphane cluster **1**. Its pseudo I_h metal core (see Figure 1) consists of a central Pd atom surrounded by 12 Pd atoms (shell 1), which in turn are encapsulated by 42 Pd atoms (shell 2), which in turn are encapsulated by 60 Pd atoms (shell 3). Thirty additional Pd atoms cap the 30 square polygons of the third-shell polyhedron with a triethylphosphane ligand attached to each capping Pd atom. It is currently presumed that 60 CO groups (crystal-disordered) edge-bridge the 30 capping Pd atoms with one-half of the square basal Pd atoms (in accordance with an IR carbonyl spectrum). The diameter of the entire Pd_{145} core of **1** between two centrosymmetrically opposite capping Pd atoms is 1.65 nm; the spherical-like geometry of the centered three-shell Pd_{115} kernel (that is, without the 30 capping Pd atoms) is evidenced by the similarity of the corresponding distances for the centrosymmetrically opposite pentagonal faces (1.22 nm), square faces (1.27 nm), and triangular faces (1.27 nm) of the third shell.

This remarkable Pd_{145} nanocluster, whose metal-core geometry was unambiguously characterized from complete crystallographic analyses of X-ray data for two crystals (from different preparations, crystals A and B),[1, 2] was isolated from the reduction of a monomeric square-planar palladium precursor, $[Pd(PEt_3)_2Cl_2]$.[3, 4] The geometrical conformity of the 55 interior metal atoms within the third shell of **1** to the well-known two-shell icosahedral Mackay hard-sphere model[5] had not been previously observed in single-crystal X-ray crystallographic determinations.[6, 7] The third-shell polyhedron in this unprecedented close-packed multi-shell metal carbonyl cluster possesses 60 equivalent vertices along with 12 pentagonal, 20 equilateral triangular, and 30 square faces;[8] this semi-regular (Archimedean) polyhedron, named rhombicosidodecahedron (with Schläfli symbol 3.4.5.4),[9] is a heretofore crystallographically unknown stereoisomer of the universally familiar C_{60} buckyball, an icosahedrally truncated semi-regular polyhedron of I_h symmetry with 60 equivalent vertices and 12 pentagonal and 20 hexagonal faces.

Because the formation of **1** is extremely sensitive to reaction boundary conditions, extensive systematic preparative efforts have been made during the last 24 months to provide a reproducible but (as yet) low-yield synthesis. The Goddess Fortuna recently revisited our laboratory in that crystals of **1** were again isolated and its crystal structure redetermined. The fact that **1** has 55 interior Pd atoms makes it an ideal model for experimental operational tests of previous interpretations of size-dependent physical properties (attributed to quantum-size effects) reported[10] for several giant noncrystalline, (N,O)-ligated, full-shell palladium clusters (ideally formulated from other measurements as five-shell Pd_{561} species by the Moiseev and Schmid groups[11, 12] and as seven-/eight-shell Pd_{1415}/Pd_{2057} species by Schmid et al[13]) and for larger Pd (colloid) particles.

That the 115-atom 3-shell core of **1** (i.e., minus the 30 capping atoms) was actually proposed by Farges et al.[14] as a possible full-shell structural model for noble-gas clusters produced in free-jet expansion into a vacuum is somewhat astonishing (i.e., mass spectra of charged noble-gas clusters provide no subshell magic-number evidence for the 115-atom cluster being particularly abundant because of special stability[14, 15]). Their model represents a geometrical modification of the classic Mackay hard-sphere multilayer icosahedral (MIC) models based upon a 13-atom centered icosahedron being considered as 20 identical (slightly distorted) *fcc* tetrahedra that share a common vertex and are connected to one another through adjacent shared faces.

Formation of the Mackay 55-atom 2-shell MIC model arises from each of the 20 tetrahedra adding a 6-atom ν_2 triangle to its 3-atom ν_1 triangular surface (111) face. The resulting second complete MIC shell ($n = 2$) consists of 42 atoms, that may originate from the addition of 30 atoms to the midpoints of the 30 edges of a 12-atom icosahedron in the second shell. In general, the number of atoms in a complete n^{th} shell is given

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