Metallo-Cryptophanes Decorated with Bis-N-Heterocyclic Carbene Ligands: Self-Assembly and Guest Uptake into a Nonporous Crystalline Lattice

James J. Henkelis,† Christopher J. Carruthers,† Scott E. Chambers,† Rob Clowes,‡ Andrew I. Cooper,† Julie Fisher,† and Michaela J. Hardie†‡

†School of Chemistry, University of Leeds, Leeds LS2 9JT, United Kingdom
‡Department of Chemistry, University of Liverpool, Liverpool, L69 7ZD, United Kingdom

Supporting Information

ABSTRACT: Pd3L2 metallo-cryptophane cages with cyclotriveratrylene-type L ligands can be stabilized by use of a bis-N-heterocyclic carbene as an auxiliary cis-protecting ligand, while use of more common protecting chelating ligands such as ethylenediamine saw a Pd3L2 to Pd6L8 rearrangement occur in solution. The crystalline Pd3L2 complexes act as sponges, taking up 1,2-dichlorobenzene or iodine in a single-crystal-to-single-crystal fashion despite not exhibiting conventional porosity.

Metallo-cages are discrete 3D polyhedral or prismatic chemical architectures that result from the self-assembly of metal cations with bridging ligands.1 Cage assemblies have cavities where other molecules may be bound and metallo-cages may behave as nanoscale reaction vessels for chemical applications such as the trapping of reactive species and enabling unusual reactivities and catalysis.1 The majority of such studies have been performed in the solution state, however the use of 3D-linked arrays of metallo-cages as solid-state nanovessels is also known.2 One of the central tenets in the design of self-assembled metallo-cage species is that the available metal coordination sites can be controlled using a chelating or macrocyclic ligand that will not be easily displaced by bridging monodentate ligands.3 Thus, in complexes such as [Pd(en)- (NO3)2] where en = ethylenediamine, the square planar Pd(II) is cis-protected with two orthogonal binding sites available. Other chelating ligands used for such cis-protection include 2,2'-bipyridines and bis-phosphine ligands.1 We report herein a system where the use of N-donor chelating ligands as cisp-protection agents fails and introduce instead chelating bis-N-heterocyclic carbene ligands for this purpose.

Our work in metallo-cages focuses on species constructed from chiral tripodal cavitands with a cyclotrimeratrylene scaffold.4,5 The simplest of these are M3L2 metallo-cryptophanes which are trinodal bipyramidal cages with substantial internal space, first reported by Shinkai and Yamaguchi from the self-assembly of a tris(4-pyridyl)-functionalized cavitant with the cis-protected [Pd(PPh3)2(CH2=CH2PPh3)2(O Tf)2]6 M3L2 cages may also form from other classes of tripodal ligands.7 The ligands L1–L4 all feature 4-pyridyl donor groups: (+)-L1 and (±)-L2 have been previously reported5a,8 and the novel ligands (±)-L3 and (±)-L4 were synthesized from reaction of cyclotriguaiacylene with the appropriate acid chloride (see SI). Self-assembly of (±)-L1 with [Pd(en)(NO3)2] in dimethyl sulfoxide (DMSO) was anticipated to form a [Pd3(en)3(L1)2]6+ metallo-cryptophane species in accordance with Shinkai and Yamaguchi’s work. Initially this was successful. Electrospray mass spectrometry (ES-MS) gave m/z peaks at 766.8358 and 1181.2525 corresponding with species {[Pd3(en)3(L1)]2-3-(NO3)3}5+ and {[Pd3(en)3(L1)]2-4(NO3)3}5+, respectively. 1H NMR data were also consistent with formation of the [Pd3(en)3(L1)]6+ assembly with a symmetric spectrum showing coordination-induced shifts for L1 and cross-coupling apparent between the en amine and L1 pyridyl (see SI). The [Pd3(en)3(L1)]6+ metallo-cryptophane, however, is metastable, and standing the solution at room temperature for 2 weeks results in a complete rearrangement to [Pd3(L1)8]12+ as the metallo-cage species in solution, Scheme 1. We have previously reported [Pd3(L1)4]12+ which has a near spherical, stella octangula architecture,5a whose [Pd3(L2)4]12+ analogue has been shown to bind large surfactant anions.6b Crystallization resulted in isolation of [Pd3(L1)8](NO3)12. Similar behavior was observed for L1 with Pd(bpy)(NO3)2 (bpy = 2,2’-bipyridine) and with Pt(en)(NO3)2. Chand has reported a very similar ligand-exchange process for the trinodal prismatic cage species [Pd3(en)3(tpb)2]6+ where tpb = 1,3,5-tris(4-pyridylmethyl)benzene.9 They reported that heating a DMSO solution of [Pd3(en)3(L1)]6+ resulted in a complete trans-
formation to sphere-like [Pd₄(tpb)]⁶⁺ and [Pd(en)]²⁺ in solution. These rearrangements may be entropically driven, as there are more cationic species in the rearranged system, and the [Pd₄(L₁)₈]²⁺ species has higher octahedral symmetry consistent with the notions of entropy of symmetry.¹⁰

In order to stabilize the smaller M₃L₂ assembly which features a potential guest binding space more suited to smaller guests, we considered chelating ligands that would be considerably less labile than the N-donor en or bpy, namely bis-N-heterocyclic carbene ligands. Bis-N-heterocyclic carbene ligands are well-known strong σ-donor ligands,¹¹ although their use as protecting groups for 3D cage assembly has not been previously explored.¹² The palladated precursor [Pd(NCMe)₂(bis-NHC-nap)]·2BF₄, where bis-NHC-nap is a 2-naphthylene derived bis-N-heterocyclic carbene, (Scheme 2) was synthesized in three steps from 1,1’-methylenebis-1H-imidazole (see SI).

Scheme 2. Self-Assembly of Cage 1 = syn-[Pd₃(bis-NHC-nap)₃(L₁)₂]⁶⁺

Reaction of 3 equiv of [Pd(NCMe)₂(bis-NHC-nap)]·2BF₄ with 2 equiv of (±)-L1 in nitromethane gives rapid formation of the metallo-cryptophane 1 in solution, Scheme 2, where 1 = [Pd₃(bis-NHC-nap)₃(L₁)₂]⁶⁺. Peaks in the ES-MS at m/z 848.2383, 1159.9853, and 1783.4759 were attributed to the species {1-2(BF₄)}⁴⁺, {1-3(BF₄)}³⁺, and {1-4(BF₄)}²⁺ respectively. ¹H NMR in d₄-MeNO₂ showed a slight downfield shift of H² of L1 and significant upfield shift of H⁸ from 7.99 to 7.43 ppm. This shielding is indicative of solution-phase π-π stacking interactions between the electron-poor and electron-rich π-rings of the pyridyl of L1 and naphthyl of the bis-NHC-nap groups. The 2D NOESY NMR spectrum shows through space correlation between H⁸ of L1 and one of the diastereotopic H⁸ protons of the bis-NHC-nap and between H⁸ of the cyclooctatetraene core of L1 and the naphthyl H⁸ and H⁹ of the bis-NHC-nap ligand. DOSY NMR measurements indicated the presence of a single large species in solution with a hydrodynamic radius of 14.4 Å. Unlike for the metastable [Pd₄(en)]₂(L₁)⁶⁺, there were no changes to the ES-MS and NMR spectra of 1 when monitored over a time period of several months, and variable temperature NMR measurements indicated no changes to 80 °C.

Comparable reactions of [Pd(NCMe)₂(bis-NHC-nap)]·2BF₄ with ligands (±)-L2, (±)-L3, or (±)-L4 led to formation of analogous metallo-cryptophanes species 2 = [Pd₃(bis-NHC-nap)₃(L₂)₂]⁶⁺, 3 = [Pd₃(bis-NHC-nap)₃(L₃)₂]⁶⁺, and 4 = [Pd₃(bis-NHC-nap)₃(L₄)₂]⁶⁺. The inherent chirality of ligands L1–L4 means that chiral anti enantiomers and the achiral syn diastereomer of metallo-cryptophanes may be formed. The ¹H NMR spectra are indicative of a single isomer in solution, identified as the syn metallo-cryptophane from single crystal X-ray structures. Single crystals of 1-6(BF₄)·8(CH₃NO₂), 2-6(BF₄)·8(CH₃NO₂), 3-6(BF₄)·8(CH₃NO₂), and 4-6(BF₄)·8(CH₃NO₂) were grown by diffusion of diethyl ether into nitromethane solutions of [Pd(NCMe)₂(bis-NHC-nap)]·2BF₄ with the appropriate ligand. The complexes are isostructural, each crystallizing in a hexagonal unit cell with their structures being solved in space group P6₃/m. The data obtained for 4-6(BF₄)·8(CH₃NO₂) were of poor resolution, hence a full structure will not be presented. The cationic cage 2 of 2-6(BF₄)·8(CH₃NO₂) is shown in Figure 1 and contains both L2 enantiomers. As anticipated, each Pd(II) center is coordinated by the chelating bis-NHC-nap ligand with Pd–C distance 1.972(9) Å and by a pyridyl group from each of two symmetry related and enantiomeric L2 ligands at Pd–N distance 2.107(9) Å. Each L2 ligand coordinates to all three Pd(II) centers of the metallo-cryptophane. Each naphthyl group of the bis-NHC-nap ligands forms face-to-face π–π stacking interactions with a pyridyl group of L2 at ring centroid separation 3.50 Å. The structures of cage 1 in 1-6(BF₄)·8(CH₃NO₂) and of cage 3 in 3-6(BF₄)·8(CH₃NO₂) are essentially the same, although the iso-nicotinoyl groups of L1 are disordered across two positions. In all cases, the L ligands align with the naphthyl groups, and the closest H–H distances between them in the crystal structures are consistent with the upfront NMR chemical shifts and observed NOE’s of the [Pd₃(bis-NHC-nap)₃(L₃)₂]⁶⁺ complexes in solution. Hence the solution- and solid-state structures of the metallo-cryptophane are the same.

The crystal lattice for complex 2-6(BF₄)·8(CH₃NO₂) is shown in Figure 2. Two BF₄⁻ anions form second-sphere interactions to Pd(II) at di-F separations 3.11 and 3.38 Å. A further BF₄⁻ anion forms multiple B–F–H–C hydrogen-bonding interactions to the backbone imidazole protons of the bis-NHC-nap...
ligands of six cages (see SI). Crystalization of the metallo- 
cryptophane cations did not occur with counter-anions PF6−,
NO3−, ClO4−, nor ReO4− in place of BF4−. Thermogravimetric
analysis (TGA) of 1·6(BF4)·8(CH3NO2) indicates the lattice
contains eight molecules of nitromethane per cage, with only
four located crystallographically, and none of these are
inside the cage. The interior cavity of the cage is 697 Å3, which is sufficient
space for the additional solvent to reside inside. This has been taken as the level of solvation for all the isostructural complexes.

Suspension of crystals of 1·6(BF4)·8(CH3NO2) in 1,2-
dichlorobenzene leads to the uptake of 1,2-dichlorobenzene by the crystal lattice despite there being no sizable channels apparent. Crystals were suspended in 1,2-dichlorobenzene for 2 weeks, isolated, washed thoroughly with diethyl ether, and air-
dried. 1H NMR of the crystals redissolved in CD3NO2 clearly shows the presence of 1,2-dichlorobenzene and the intact cage 1 in an approximate 3:1 ratio. Similar experiments with crystals of 1·6(BF4)·8(CH3NO2) that had been heated under vacuum prior to submersion gave similar levels of uptake by NMR. EDX analysis of the crystals also gives a Pd:Cl ratio that is consistent with three molecules of 1,2-dichlorobenzene per cage 1. TGA is consistent with fewer nitromethane molecules in the lattice compared with the parent 1·6(BF4)·8(CH3NO2), again supporting solvent exchange of 1,2-dichlorobenzene.

This process occurs in a single crystal-to-single crystal (SCTSC) fashion, and the crystal structure of the daughter complex 1·6(BF4)·5(CH3NO2)·3(C6H4Cl2) is isomorphic with the parent complex 1·6(BF4)·8(CH3NO2). Positions of the absorbed 1,2-dichlorobenzene molecules were located in the crystal structure, and the [Pd4(en)3(L1)2][BF4]6+ cage is fully ordered. The 1,2-dichlorobenzene molecules show a 2-fold disorder and are not located inside the metallo-cryptophane but rather in three equivalent positions in the equatorial region outside the cage, Figure 3. The Cl moieties are directed into clefts bounded by pyridyl and propyl groups of two L1 ligands with closest Cl···C separations ~3.28 and 3.37 Å. One CH3NO2 position can be established in the crystal structure and is located in a pocket created by bis-imidazolyl moieties of three adjacent [Pd4(bis-
NHC-nap)3(L1)2][BF4]6+ cages; solvent was also located in this position in the parent crystal. The presence of four additional CH3NO2 per cage was established by TGA, and these are assumed to occupy the internal cavity of the metallo- 
cryptophane, notably this is the same degree of additional intracage solvation estimated from the TGA of the parent complex 1·6(BF4)·8(CH3NO2).

Figure 3. From the crystal structure of 1·6(BF4)·5(CH3NO2)·
(C6H4Cl2) showing disordered 1,2-dichlorobenzene (carbon atoms in orange) exo to cage 1.

The crystalline complex 2·6(BF4)·8(CH3NO2) also exhibits guest uptake behavior in a SCTSC fashion. Dichlorobenzene uptake was observed by NMR as for 1·6(BF4)·8(CH3NO2), but the resultant crystals were poorly diffracting, and a crystal structure could not be established. Crystals of 2·6(BF4)·8(CH3NO2) were soaked in an ethereal solution of iodine for a week to give complex 2·6(BF4)·(H2O)·3(I2). The level of I2 uptake was taken from EDX measurements, and Raman spectroscopy was consistent with the presence of iodine species (see SI).13 Iodine uptake into a solid-state matrix has relevance in nuclear fuel reprocessing and has been reported with framework materials such as metal—organic frameworks (MOFs)14 and, more rarely, in porous molecular crystals.15 The single crystal structure of 2·6(BF4)·(H2O)·3(I2) is isomorphic with the parent complex. There are three crystallographically distinct and partially occupied sites modeled as included I2, Figure 4. One

Figure 4. From the crystal structure of complex 2·6(BF4)·(H2O)·3(I2)
showing positions of partially occupied and disordered iodine (shown in
space-filling) exo and endo to the metallo-cryptophane.

partially occupied I2 molecule is disordered across a 3-fold rotation axis and sits within the tribenzo[adg]cyclononatriene cavity of ligand L2 with each position nearly parallel with an aryl ring at a I2···aryl centroid···centroid separation of 4.197 Å. This is very similar to I2···aryl separations observed from the uptake of I2 by a cadmium triazole MOF.14d The parent crystals also absorb iodine from the vapor phase, although at much lower levels of uptake of ~1 molecule of I2 which is absorbed into a lattice rather than intracage site (see complex 2·6(BF4)·(I2) in SI). The crystals of 2·6(BF4)·(H2O)·3(I2) do not decolorize on soaking in methanol or diethyl ether or on heating under vacuum at 80 °C for 30 min, which removes any surface I2 deposition. This is consistent with previously reported MOF systems that retain I2 within their pores on heating.14b

While the crystal lattices contain rigid, although solvent filled, spaces of the metallo-cryptophane, the lattice structure is nonporous. This is because it contains no infinite channels linking these spaces, and gas sorption studies of activated 2-
6(BF4) do not show the profiles typical of a material with significant conventional permanent porosity.16 Permanent porosity and concomitant guest exchange and sorption behavior is well-established for materials, such as MOFs where there are 3D channels in the lattice, and for some coordination cages.17 There has been considerably less attention, however, directed toward the ability of seemingly nonporous 0D structures to absorb guests as reported here. Atwood, Barbour et al. have shown that nonporous crystals of p-tert-butylcalix[4]arene can uptake guests by cooperative van der Waals confinement.18 Barbour has also reported that an apparently nonporous crystalline lattice of a metalacalycarbine can absorb gaseous guests.19 Cooper has demonstrated that Xe and Ra can diffuse through a robust lattice of organic cages despite windows between the cage pores being smaller than the diameter of the gases.20 Interestingly, preliminary experiments also showed a moderate uptake of Xe by complex 2-6(BF4), which was more pronounced than uptake of the smaller Kr (see SI). Small organic cryptophanes are well-known for binding Xe in solution,21 but these materials have potential as sequestering agents for radioactive I2. Furthermore, preliminary results indicate an uptake of 60Co.3

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[**ASSOCIATED CONTENT**](#)

- Supporting Information
- Full experimental procedures, spectra, TGA traces, and crystallography. This material is available free of charge via the Internet at http://pubs.acs.org.

[**AUTHOR INFORMATION**](#)

**Corresponding Author**
m.j.hardie@leeds.ac.uk

**Notes**
The authors declare no competing financial interest.

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