

Flexible Bidentate Pyridine and Chiral Ligands in the Self-Assembly of Supramolecular 3-D Cages

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Abstract: Discrete, nanoscopic 3-D cages are prepared in high yield via coordination-driven self-assembly from a variety of building blocks, including bidentate 3-substituted pyridines, chiral, and silicon-based tripods. All are characterized by NMR (³¹P, ¹H) and electrospray ionization mass spectrometry.

An abundance of discrete 3-D supramolecular species assembled from simple building blocks has been reported in recent years.^{1–10} Of all the noncovalent interactions, the coordination bonding motif has proven itself to be a highly useful tool for their preparation. By employing a rational transition-metal-mediated approach,¹¹ complex nanoscopic supramolecules are formed via self-assembly of appropriately designed precursors.

Recently, supramolecular prisms of *D*_{3h} symmetry were reported by our group.¹² X-ray crystallography of one cage showed a single nitrate anion incarcerated within its cavity. Likewise, new tetrahedral phosphorus and silicon-based assemblies of similar geometry and size were prepared.¹³ These achiral examples contain only rigid 4-substituted pyridine linkers which always maintain the same bonding directionality. Conversely, the nitrogen atoms of 3-substituted pyridines **2a,b** are able to adopt any dihedral angle between 0 and 180° by rotation around the central acetylene bond(s). This is illustrated by the trans-orientation of **2a** in coordination polymers

with cadmium(II) and cobalt(II) nitrate.¹⁴ This same arrangement is observed¹⁵ in polymers of **2b** with copper(II) nitrate while **2a** bonds in a cis-type fashion.¹⁴ In contrast, we have shown that reactions between less labile platinum acceptors and pyridine donors **2a,b** produce closed 2-D structures.¹⁶

We were interested in investigating (1) whether **2a,b** could be used to prepare discrete 3-D supramolecules rather than infinite networks and (2) assembling a chiral cage using tripods **1c,d**. Herein we report our results.

The formation of 3-D cages **3** is shown in Scheme 1. They are prepared by heating 2 equiv of tritopic unit **1** with 3 equiv of bidentate ligand **2** in a 1:1 acetone-*d*₆/D₂O medium at 60 °C for 24 h. The reaction progress is easily followed with ³¹P{¹H} and ¹H NMR. The ³¹P spectrum of each assembly displays a singlet (ca. 16 ppm **3a–d**, 9.81 ppm **3e,f**) shifted upfield from the starting platinum materials by 4–5 ppm. This change, as well as the decrease in coupling of the flanking ¹⁹⁵Pt satellites ($\Delta J = \text{ca. } -200 \text{ Hz}$), is consistent with back-donation from the platinum atoms. The phosphine methylene moieties also shift slightly upfield (ca. 0.3 ppm) in the ¹H spectra. The pyridine hydrogens adjacent to the nitrogen nucleus experience small shifts (ca. 0.3 ppm **3a–d**, 0.5 ppm **3e,f**) downfield due to the loss of electron density that occurs upon coordination. The central anthracene proton (H-9) of **3e,f** moves 0.5 ppm to higher field. Two sets of doublets corresponding to the phenyl (**1a,b**) and pyridyl (**1c,d**) hydrogens of each tripod are evident in the assemblies **3**. Clearly, rotation of these rings is restricted once the cage is formed, thus creating different inner and outer environments. As expected, identical spectra were recorded for each enantiomeric cage **3e,f**. In all cases the assemblies are the major products. Small amounts of oligomeric material are sometimes formed.

Satisfactory elemental analyses of **3a,c** as the nitrate salts were obtained. For the other assemblies **3b,d–f** it was necessary to precipitate them as hexafluorophosphate salts first by addition of KPF₆. This also revealed further evidence of the structure of **3e,f**. The elemental analysis revealed only five nitrate counterions had been exchanged with hexafluorophosphates. This was confirmed by using electrospray ionization mass spectrometry. Peaks attributable to the consecutive loss of hexafluorophosphate counterions, [M – 2PF₆]²⁺ (*m/z* 2216.9), [M – 3PF₆]³⁺ (*m/z* 1429.5), and [M – 4PF₆]⁴⁺ (*m/z* 1035.0), where M represents the intact 3-D cage with a single encapsulated NO₃[–], were observed in the spectrum of **3e,f**. The former was isotopically resolved and matches the theoretical distribution very well. On the basis of X-ray analysis of analogous structures,¹² it is likely the

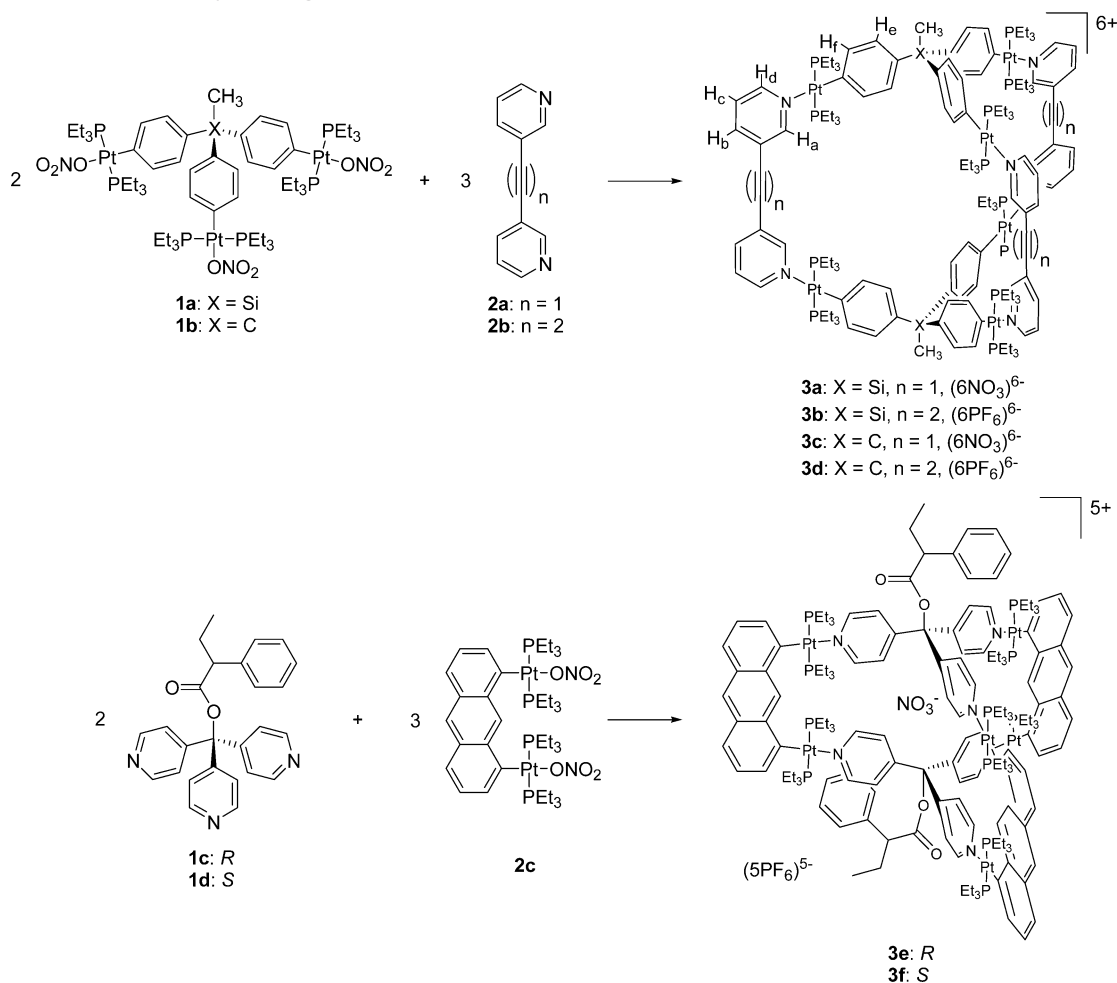
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SCHEME 1. Self-Assembly of Cages **3** from Tripods **1** and Linkers **2**

lone nitrate counterion is trapped within the molecular cavity. The molar rotation ($[\phi]_D$) of **3e** (−201) was similar in magnitude but opposite in sign to its enantiomer **3f** (+205).

Mass spectra of the other cages **3a–d** were obtained as the nitrate salts. A small peak for the $[M - 2NO_3]^{2+}$ species (m/z range 1944–1995) was isotopically resolved for each product. These were complemented by much larger peaks for the $[M - 3NO_3]^{3+}$ (m/z 1275–1310) and $[M - 4NO_3]^{4+}$ (m/z 941–967) species.

In conclusion we have prepared and characterized several nanoscopic 3-D assemblies from a variety of building blocks. Cages **3a–d** are the first examples of discrete 3-D supramolecules formed from flexible 3-substituted pyridines **2a,b** and organoplatinum reagents. Clearly **2a,b** prefer to self-assemble into closed systems despite their ability to vary their bonding directionality. Cages **3e,f** represent an additional example of the few chiral 3-D systems where both self-assembled enantiomers are prepared. Moreover, tripod **1c,d** is readily available making it a valuable building block for construction of a variety of chiral 3-D structures.

Experimental Section

Methods and Materials. 1,2-Bis(3-pyridyl)ethyne **2a**,¹⁷ 1,4-bis(3-pyridyl)-1,3-butadiyne **2b**,¹⁸ and organoplatinum compounds **1a,b**¹³ and **2c**¹⁹ were all prepared as reported.

General Procedure for the Preparation of Assemblies 3. The pyridine linker (10 μmol **1c,d**, 6 μmol **2a,b**) and platinum acceptor (4 μmol **1a,b**, 15 μmol **2c**) were placed in a 1-dram vial. Acetone-*d*₆ (0.5 mL) and D₂O (0.5 mL) were added. The vial was sealed with Teflon tape and the reaction stirred and heated in an oil bath at 60 °C for 24 h. The solution was then transferred to an NMR tube for analysis. In the case of **3a** and **3c**, the reaction was filtered and the solvent removed under a stream of N₂. The solid residue obtained was washed twice with diethyl ether then dried overnight in vacuo. In the case of **3b,d–f**, excess KPF₆ was added to precipitate the product, which was collected and washed with water then dried in vacuo.

3a: Yield 98%. Mp 156–158 °C dec. ¹H NMR (acetone-*d*₆/D₂O 1:1, 300 MHz) δ 9.11 (d, ⁴J = 1.84 Hz, 6H, H_a), 8.83 (d, ³J = 5.57 Hz, 6H, H_d), 8.26 (d, ³J = 8.30 Hz, 6H, H_b), 7.81 (dd, ³J = 8.29 Hz, ³J = 5.73 Hz, 6H, H_d), 7.38 (m, 12H, H_f and H_f'), 7.26 (d, ³J = 7.82 Hz, 6H, H_e), 6.95 (d, ³J = 7.74 Hz, 6H, H_e), 1.30 (m, 72H, PCH₂), 1.03 (m, 108H, PCH₂CH₃), 0.90 (s, 6H, Si-CH₃); ³¹P{¹H} NMR (acetone-*d*₆/D₂O 1:1, 121 MHz) δ 16.1 (s, ¹⁹⁵Pt satellites, ¹J_{Pt–P} = 2682 Hz). Anal. Calcd for C₁₄₆H₂₃₄N₁₂O₁₈P₁₂Pt₆Si₂: C, 43.36; H, 5.83; N, 4.16. Found: C, 43.46; H, 6.09; N, 3.78.

3b: Yield 96%. Mp >300 °C dec. ¹H NMR (acetone-*d*₆/D₂O 1:1, 300 MHz) δ 8.97 (d, ⁴J = 1.58 Hz, 6H, H_a), 8.84 (d, ³J = 5.29 Hz, 6H, H_d), 8.21 (d, ³J = 8.08 Hz, 6H, H_b), 7.79 (dd, ³J = 8.16

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Hz, $^3J = 5.77$ Hz, 6H, H_c), 7.35 (d, $^3J = 7.61$ Hz, 6H, H_f or H_{f'}), 7.31 (d, $^3J = 7.61$ Hz, 6H, H_{f'} or H_f), 7.24 (d, $^3J = 7.49$ Hz, 6H, H_e or H_{e'}), 6.81 (d, $^3J = 7.63$ Hz, 6H, H_{e'} or H_e), 1.27 (m, 72H, PCH₂), 1.00 (m, 108H, PCH₂CH₃), 0.87 (s, 6H, Si-CH₃); $^{31}\text{P}\{^1\text{H}\}$ NMR (acetone-*d*₆/D₂O 1:1, 121 MHz) δ 16.8 (s, ^{195}Pt satellites, $^1J_{\text{Pt-P}} = 2672$ Hz). Anal. Calcd for C₁₅₂H₂₃₄F₃₆N₆P₁₈Pt₆Si₂: C, 39.57; H, 5.11; N, 1.82. Found: C, 39.73; H, 5.23; N, 1.80.

3c: Yield 99%. Mp >200 °C dec. ^1H NMR (acetone-*d*₆/D₂O 1:1, 300 MHz) δ 9.04 (d, $^4J = 1.57$ Hz, 6H, H_a), 8.81 (d, $^3J = 5.62$ Hz, 6H, H_d), 8.23 (d, $^3J = 8.16$ Hz, 6H, H_b), 7.81 (dd, $^3J = 8.16$ Hz, $^3J = 5.61$ Hz, 6H, H_c), 7.27 (d, $^3J = 7.99$ Hz, 6H, H_f or H_{f'}), 7.13 (m, 12H, 6H_{f'} or 6H_f and 6H_e or 6H_{e'}), 6.31 (d, $^3J = 7.99$ Hz, 6H, H_{e'} or H_e), 2.20 (s, 6H, C-CH₃), 1.32 (m, 72H, PCH₂), 1.03 (m, 108H, PCH₂CH₃); $^{31}\text{P}\{^1\text{H}\}$ NMR (acetone-*d*₆/D₂O 1:1, 121 MHz) δ 16.3 (s, ^{195}Pt satellites, $^1J_{\text{Pt-P}} = 2696$ Hz). Anal. Calcd for C₁₄₈H₂₃₆N₁₂O₁₉P₁₂Pt₆·H₂O: C, 44.11; H, 5.90; N, 4.17. Found: C, 44.31; H, 5.88; N, 4.19.

3d: Yield 96%. Mp >300 °C dec. ^1H NMR (acetone-*d*₆/D₂O 1:1, 300 MHz) δ 9.05 (d, $^4J = 1.64$ Hz, 6H, H_a), 8.86 (d, $^3J = 5.46$ Hz, 6H, H_d), 8.23 (d, $^3J = 8.26$ Hz, 6H, H_b), 7.81 (dd, $^3J = 8.19$ Hz, $^3J = 5.69$ Hz, 6H, H_c), 7.28 (d, $^3J = 8.27$ Hz, 6H, H_f or H_{f'}), 7.15 (m, 12H, 6H_{f'} or 6H_f and 6H_e or 6H_{e'}), 6.27 (d, $^3J = 8.01$ Hz, 6H, H_{e'} or H_e), 2.24 (s, 6H, C-CH₃), 1.32 (m, 72H, PCH₂), 1.03 (m, 108H, PCH₂CH₃); $^{31}\text{P}\{^1\text{H}\}$ NMR (acetone-*d*₆/D₂O 1:1, 121 MHz) δ 16.3 (s, ^{195}Pt satellites, $^1J_{\text{Pt-P}} = 2685$ Hz). Anal. Calcd C₁₅₄H₂₃₄F₃₆N₆P₁₈Pt₆: C, 40.37; H, 5.15; N, 1.83. Found: C, 40.45; H, 5.19; N, 1.88.

3e-f: Yield 91% of **3e**; 89% of **3f**. Mp 256–258 °C dec. $[\alpha]_{\text{D}} -4.25$ (**3e**), +4.34 (**3f**); $[\phi]_{\text{D}} -201$ (**3e**), +205 (**3f**). ^1H NMR (acetone-*d*₆/D₂O 1:1, 300 MHz) δ 8.96 (m, 12H, H _{α -Py}), 8.91 (s, 3H, H₉), 8.35 (s, 3H, H₁₀), 7.82 (br d, $^3J = 4.22$ Hz, 6H, H _{β -Py}), 7.70 (m, 18H, H _{β -Py} and H_{2,4,5,7}), 7.41 (s, 10H, H_{phenyl}), 7.12 (t, 6H, $^3J = 7.44$ Hz, H_{3,6}), 4.22 (t, 2H, $^3J = 7.74$ Hz, C(O)-CH), 2.20 (m, 2H, C(O)-CH(Ph)-CHH), 1.90 (m, 2H, C(O)-CH(Ph)-CHH), 1.34 (m, 72H, P-CH₂), 0.82 (m, 114H, P-CH₂-CH₃ and C(O)-CH(Ph)-CH₂-CH₃); $^{31}\text{P}\{^1\text{H}\}$ NMR (acetone-*d*₆/D₂O 1:1, 121 MHz) δ 9.81 (s, ^{195}Pt satellites, $^1J_{\text{Pt-P}} = 2639$ Hz). Anal. Calcd for C₁₆₆H₂₅₀F₃₀N₇O₇P₁₇Pt₆: C, 42.22; H, 5.34; N, 2.08. Found: C, 42.17; H, 5.25; N, 2.15.

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Supporting Information Available: Experimental procedure for the synthesis of **1c,d** and NMR and mass spectral data for assemblies **3**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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