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Self-Assembly of Tripyrazolate-Linked Macrotricyclic $M_{12}L_4$ Cages with Dimetallic Clips

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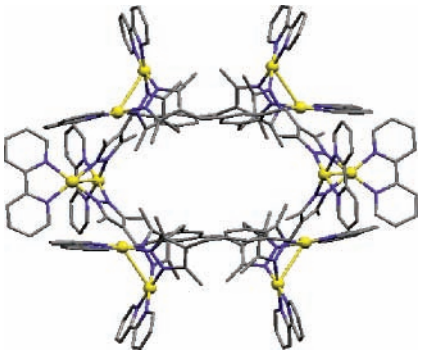
ABSTRACT



The self-assembly in aqueous solution of tripyrazolate trianion linkers (H_3L = 1 and 2) with coordinated dimetallic clips leads to the formation of $Pd_{12}L_4$ cages with interior cavities of 1800 Å^3 and 1500 Å^3, respectively, confirmed by ^{1}H NMR, ^{13}C NMR, cold spray ionization mass spectrometry (CSI-MS), and single-crystal X-ray analysis.

The three-dimensional (3D) cages with large interior cavities have increasingly attracted interest in the areas of supramolecular chemistry, host−guest complexation, and biological mimicry.[1,2] However, the construction of such complex frameworks by conventional synthetic strategies is very laborious. Over the past decade, it has become feasible to efficiently prepare 3D cages with inner nanospaces through noncovalent self-organization and self-assembly approaches.[3−8]

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Noticeably, self-assembly via directional metal coordination has led to the fabrication of well-defined 3D cages[9−16] that exhibit potential applications in molecular encapsulation,[17] transformation, catalysis, and organic synthesis.[18] In order to develop structurally and functionally new 3D cage-like architectures, de novo design and synthesis of organic ligands and rational choice of coordination motifs are crucial.

In view of the variety of potential applications of pyrazolate-bridged multimetal coordination compounds,[19] we have recently reported the solution self-assembly of two-dimensional (2D) metallomacrocyclic complexes with linear bipyrazolate dianion linkers[20] and coordinated dimetallic clips (Figure 1). Along this approach, it can be expected that the

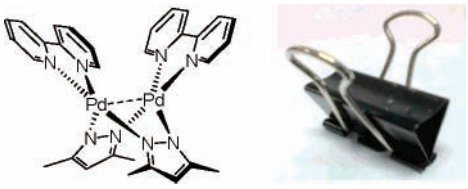
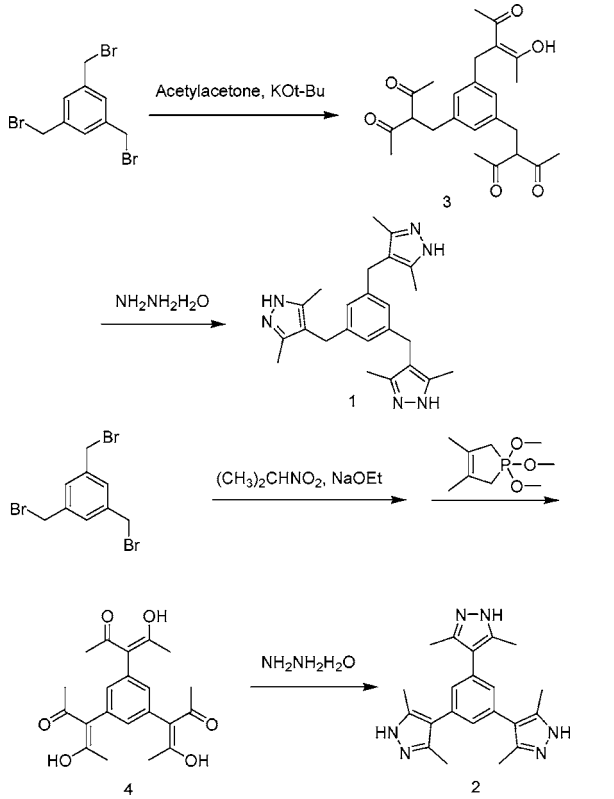


Figure 1. Representation of a coordinated dimetallic clip.

polypyrazolate ligands, such as tripyrazolate trianion linkers, may give rise to more fascinating 3D supramolecular architectures. Although a number of cagelike structures[9−16] built from various organic linkers and metal centers with different coordination motifs have been reported during the past decade, the pyrazolate-bridged 3D cages with coordinated dimetallic clips are rare to date. Herein, we report the synthesis of tripodal tripyrazolate linkers **1** and **2** and their utilities in the self-assembly of 3D macrotricyclic cages in aqueous solution.

Linkers **1** and **2** were synthesized as shown in Scheme 1. The 1,3,5-tris(bromomethyl)benzene was stirred and refluxed

Scheme 1. Synthesis of Tripyrazolate Linkers **1** and **2**



with KO-*t*-Bu and acetylacetone in THF to give **3** (40%).[21] This compound was treated with hydrazine hydrate in ethanol at room temperature to afford 1,3,5-tri((3,5-dimethyl-1*H*-pyrazol-4-yl)methyl)benzene **1** as a white powder (89%). Compound **2** was synthesized by different route from that of **1**. The 1,3,5-tris(bromomethyl)benzene was reacted with 2-nitropropane and NaOEt in ethanol/DMSO mixed solvent, following treatment with 2,2,2-trimethoxy-4,5-dimethyl-1,3,2-dioxaphospholene to produce **4** (10%).[22] Similarly, compound **4** was then condensed with hydrazine hydrate in ethanol at room temperature to afford 1,3,5-tri(3,5-dimethyl-1*H*-pyrazol-4-yl)benzene **2** as white powder (85%). The linkers **1** and **2** were identified by ^{1}H and ^{13}C NMR, MALDI-TOF mass spectral evidence ($[M + H^+]^+$= 403.5 and 361.3 for **1** and **2**, respectively) and element analyses.

As shown in Scheme 2, the combination of **1** and the [(bpy)Pd(NO_3)$_2$] in a 1:3 ratio in water at room temperature gives rise to the self-assembly of the macrotricyclic cage

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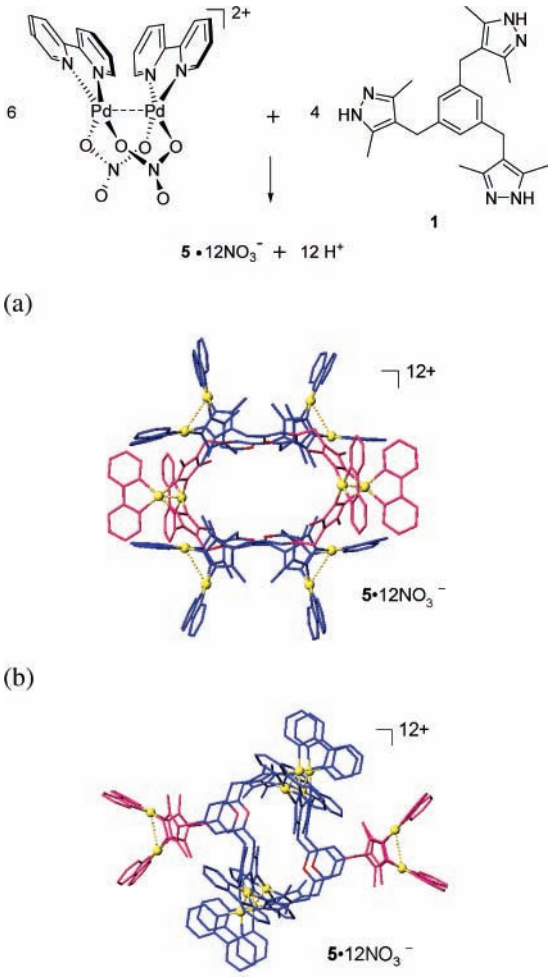
Scheme 2. Self-Assembly and Crystal Structure of Macrotricyclic Cage **5**: (a) Side View, (b) Top View (Hydrogen Atoms Are Omitted for Clarity)



{[(bpy)Pd]$_{12}$L$_4$}(NO$_3$)$_{12}$ (**5**•12NO$_3^-$, where H$_3$L = **1**) in quantitative yield. Analysis by ^{1}H NMR spectroscopy of its deuterated aqueous solution clearly shows a dispersed array of well-defined resonance and suggests the self-assembly of linker **1** and [(bpy)Pd(NO$_3$)$_2$] to form a single product (Figure 2). All of the signals in the spectrum could be respectively ascribed to four kinds of protons, namely Bpy-H, Phenyl-H, Methylene-H, and Methyl-H. Significantly, the integrations of two nonequivalent protons of above each group are present in a 2:1 ratio in the self-assembly product, which are marked with blue and red arrows in Figure 2 (e.g., for Methyl-H, δ= 2.8 and 3.2, for Phenyl-H, δ= 6.6 and 7.6). Therefore, the ^{1}H NMR data are fully consistent with the macrotricyclic structure of **5**; that is, the pyrazolyl groups drawn in blue and red in Scheme 2 are not equivalent. This result indicates that the low symmetric geometry of compound **5** induces two different microenvironments for the same kind of groups and is parallel to those observed by Fujita et al.[23] More interestingly, the proton signals of methylene groups contained two sets of multiplets, which results from the high distortion of methylene groups between the phenyl cycle and pyrazolyl group. This result suggests that the presence of the dimetallic coordination clips restricts the mobility of pyrazolyl groups and increases the rigidity of the macrotricyclic framework, as revealed by X-ray structure analysis of the cage in the solid state.

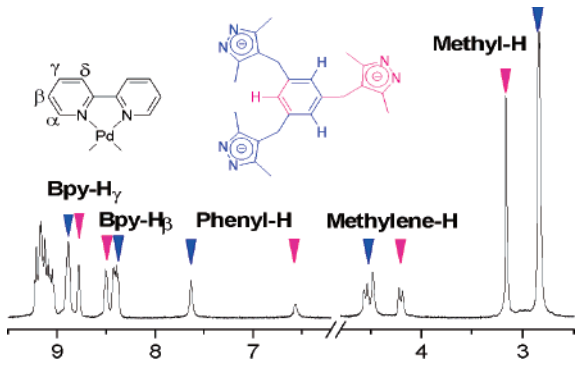


Figure 2. ^{1}H NMR of macrotricyclic cage **5**•12NO$_3^-$.

Although NMR considerations allowed us to conclusively determine the structure of macrotricyclic cage **5**, we were also able to obtain CSI-MS for this complex (Figure 3).

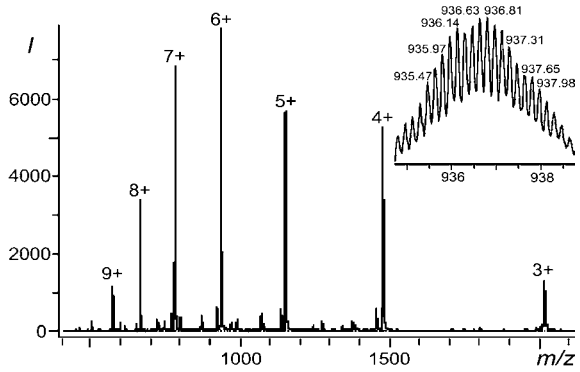


Figure 3. CSI MS and the isotopic distribution of the species [**5**•6PF$_6^-$]$^{6+}$ (inset) of macrotricyclic cage **5**•12PF$_6^-$.

Complex **5**•12NO$_3^-$ was isolated as its hexafluorophosphate salt **5**•12PF$_6^-$; by precipitated with excessive KPF$_6$. The CSI-MS spectra of **5**•12PF$_6^-$ in acetonitrile showed prominent peaks attributable to the consecutive loss of PF$_6^-$ counterions. The mass to charge ratio (*m*/*z*) peaks 504.0, 576.2, 666.3, 782.3, 936.6, 1153.0, 1477.5 and 2018.0 for [**5**•2PF$_6^-$]$^{10+}$, [**5**•3PF$_6^-$]$^{9+}$, [**5**•4PF$_6^-$]$^{8+}$, [**5**•5PF$_6^-$]$^{7+}$, [**5**•6PF$_6^-$]$^{6+}$, [**5**•7PF$_6^-$]$^{5+}$, [**5**•8PF$_6^-$]$^{4+}$, and [**5**•9PF$_6^-$]$^{3+}$, respectively (Figure 2), are in good agreement with theoretical values.

Further support of the structure of **5**•12PF$_6^-$ was obtained by single-crystal X-ray analysis. As shown in Scheme 2a,b, complex **5**•12PF$_6^-$ crystallizes in the triclinic space group *P*-1 with 20 cocrystallized water molecules. The molecular

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dimensions are approximately 28 × 24 × 22 Å, and the dimensions of the inner cavity are roughly 20.4 × 10.3 × 8.5 Å. The interior void of about 1800 Å^3 is estimated. The crystal structure analysis for **5**·12PF_6^- revealed the dihedral angles between coordination planes of the bpy linkers are 81.2° (Pd1 and Pd2), 82.3° (Pd3 and Pd4), and 89.8° (Pd5 and Pd6), respectively. Because of the large dihedral angles, there are no $\pi\cdots\pi$ interactions between the bpy ligands coordination planes. The separation of Pd1···Pd2 (3.187 Å), (Pd3···Pd4) (3.182 Å), and Pd5···Pd6 (3.191 Å) are near the sum of van der Waals radii of palladium (the typical value is 1.6 Å), which reveals quite weak Pd···Pd interaction. The PF_6^- anions in the crystal are located outside the cavity and adjacent to the Bpy ligands by hydrogen bonds of C−H···F. Interestingly, it was also found that the macrotricyclic components could pack into tubular channel with the wall containing the linkers and the bpy aromatic rings, which extended in the crystallographic *a*, *b*, and *c* axes with PF_6^- anions frozen inside.

Similarly, mixing linker **2** with [(bpy)Pd$(NO_3)_2$] in a 1:3 molar ratio in water−acetone (1:1) also results in the formation of the macrotricyclic cage {[(bpy)Pd]$_{12}$L$_4$}(NO3)$_{12}$ (**6**·12NO_3^-, where H_3L = **2**) in quantitative yield at room temperature. The ^{1}H NMR spectroscopy unambiguously shows that a complex with a 3:1 molar ratio of (bpy)Pd to **2** is formed (Figure 4). Having similar resonance pattern to **5**, the spectrum also shows a 2:1 ratio of two nonequivalent Phenyl-H and Bpy-H. The structure of macrotricyclic cage **6** was further confirmed by CSI−MS. Addition of excessive KPF_6 to aqueous solution of complex **6**·12NO_3^- results in precipitation of **6**·12PF_6^- in quantitative yield. In the CSI−MS spectra for **6**·12PF_6^- in acetonitrile, the *m*/*z* peaks are attributed to 3015.8, 1961.9, 1435.2, 1119.0, 908.4, 757.5 and 645.0 for [**6**·10PF_6^-]$^{2+}$, [**6**·9PF_6^-]$^{3+}$, [**6**·8PF_6^-]$^{4+}$, [**6**·7PF_6^-]$^{5+}$, [**6**·6PF_6^-]$^{6+}$, [**6**·5PF_6^-]$^{7+}$, and [**6**·4PF_6^-]$^{8+}$, respectively, and accurately consistent with theoretical values.

According to the data, complex **6** should have the same macrotricyclic topology.[23] Therefore, a visual molecular model was computed using *CAChe* program 6.1.1[24] to evaluate the size and shape of macrotricyclic cage **6** (Figure 4). Because the arms of linker **2** were shorter and more rigid than those of **1**, cage **6** possesses smaller molecular dimension and inner cavity, 27 × 26 × 20 Å and 13 × 13 × 9 Å, respectively.

In summary, we describe the synthesis of the tripyrazolate trianion linkers **1** and **2** through different synthetic strategies, and their successful application to build novel 3D macrotricyclic cages **5** and **6** with coordinated dimetallic clips by means of coordination-driven self-assembly. These assemblies have been well-characterized by ^{1}H NMR, ^{13}C NMR, and CSI-MS in solution and, in the case of **5**, by single-crystal X-ray analysis. The preparation of more complex architectures based on related poly pyrazolate anionic linkers with homo- or hetero- dimetallic clips beyond palladium is currently pursued in our laboratory, as is the cavity-directed synthesis and dimetallic coordination catalysis within the 3D nanocages.

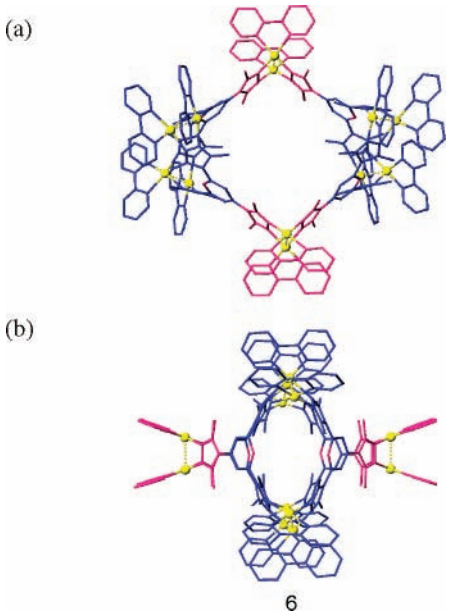

Figure 4. Ball-and-stick model of cage **6** computed with the CAChe 6.1.1 program: (a) side view; (b) top view (hydrogen atoms are omitted for clarity).

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Supporting Information Available: Experiments procedures and the characterizaiton of for linkers **1** and **2** and compounds **5** and **6**. This material is available free of charge via the Internet at http://pubs.acs.org.

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