JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
pubs.acs.org/JACS

$M_{12}L_{24}$ Spheres with Endo and Exo Coordination Sites: Scaffolds for Non-Covalent Functionalization

Kate Harris, Qing-Fu Sun, Sota Sato, and Makoto Fujita*

Department of Applied Chemistry, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

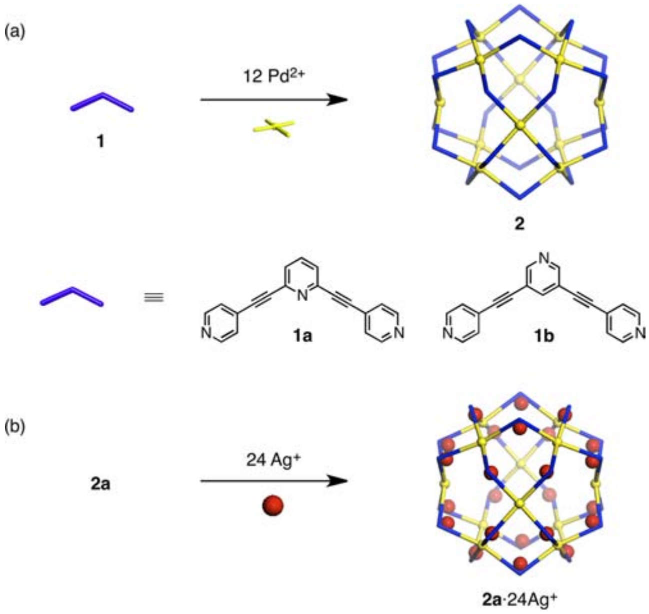
Supporting Information

ABSTRACT: $M_{12}L_{24}$ spherical complexes incorporating 24 free pyridine rings on their interior or exterior surfaces were synthesized via the self-assembly of tridentate tris(pyridine) ligands with Pd^{2+} ions. Coordination of secondary metal ions in the interior of the spherical framework was achieved through interactions of 24 Ag^+ ions with the free endo pyridine rings.

The prevalence of structures assembled from multiple repeating subunits in nature has inspired chemists to construct artificial hollow coordination complexes of ever-increasing complexity from multiple identical components.[1] However, while biological structures are highly functionalized and interact with their environment through weak non-covalent interactions, the functionality of artificial self-assembled hollow complexes is still limited. The cavities of artificial hollow complexes can often encapsulate guest molecules and promote unusual reactivity,[2−7] but the interactions between the cage and the guests are primarily hydrophobic in nature. In fact, the nature of the organic ligand often precludes the incorporation of appended functional groups. A notable exception to this is the family of M_nL_{2n} polyhedral coordination spheres,[8,9] and the endo and exo functionalization of the $M_{12}L_{24}$ spherical framework with 24 identical functional groups is now well-established. Similar exo functionalization has been reported for other spherical complexes.[10,11] In all cases, however, the desired functional side chain is covalently introduced at the concave/convex position of the bent ligand prior to self-assembly of the spherical complex. The only example of non-covalent functionalization is the peripheral functionalization of spherical polyanionic polyoxometalates with organic cations.[12] Here we report the self-assembly of $M_{12}L_{24}$ spheres containing 24 free pyridine rings on their interior or exterior surfaces and demonstrate the coordination of metal ions to their open endo binding sites (Scheme 1).

Tridentate ligands **1**,[13,14] which were previously employed by Stang for the self-assembly of macrocycles and polygons, were used in this study. When **1a** was heated with 0.55 equiv of $Pd(BF_4)_2{\cdot}4MeCN$ in perdeuterated dimethyl sulfoxide (DMSO-d_6) at 70 °C for 2.5 h, a single species with high symmetry, **2a**, was obtained, as observed by ^1H NMR spectroscopy. In the ^1H NMR spectrum of **2a** (Figure 1b), only the terminal pyridyl signals were shifted significantly downfield [$\Delta\delta(H^a) = +0.53$ ppm; $\Delta\delta(H^b) = +0.31$ ppm] relative to those for **1a** (Figure 1a); the chemical shifts for the protons of the central pyridine remained essentially unchanged [$\Delta\delta(H^c) = +0.00$ ppm; $\Delta\delta(H^d) = +0.03$ ppm]. These observations suggested that only the terminal pyridyl moieties underwent metal coordination and that the central pyridine nitrogen remained uncoordinated in the final product. Diffusion-ordered NMR spectroscopy (DOSY) also indicated the formation of a single product with a diffusion coefficient (D) of 3.98×10^{-11} m^2 s^{-1} ($\log D = -10.4$) at 300 K in DMSO-d_6 (Figure 1f). This value is consistent with those for previously reported $M_{12}L_{24}$ complexes with the same shell framework[15−17] and the diameter of 4.6 nm estimated from molecular modeling. Confirmation of the $M_{12}L_{24}$ composition of sphere **2a** came from cold-spray ionization time-of-flight mass spectrometry (CSI-TOF MS), in which a series of peaks was observed for $[Pd_{12}\mathbf{1a}_{24}{\cdot}(BF_4)_{24} - nBF_4]^{n+}$ ($n = 8{-}12$).

Scheme 1. (a) Self-Assembly of $M_{12}L_{24}$ Spheres Containing 24 Free Pyridine Rings and (b) Their Non-Covalent Functionalization by Coordination of Ag^+ Ions



On the basis of partial charge calculations (see the Supporting Information), the terminal and central pyridine moieties of **1b** are expected to have similar coordination abilities. Nevertheless, a single product with the same diffusion coefficient as **2a** ($\log D =$

Received: May 12, 2013
Published: August 9, 2013

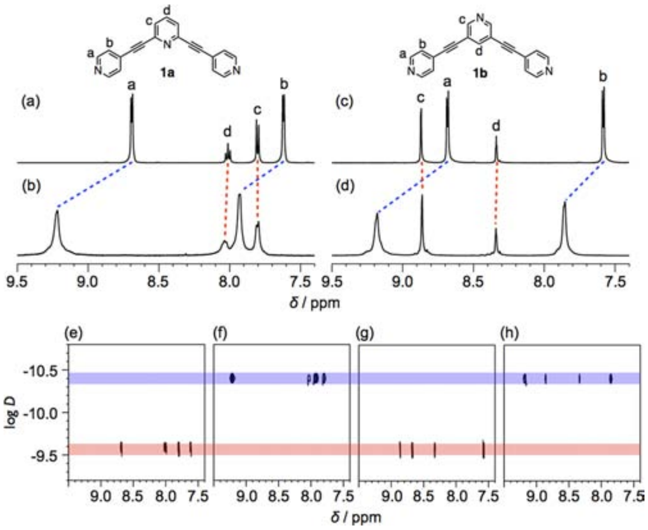


Figure 1. (a−d) ^{1}H NMR spectra of (a) **1a**, (b) **2a**, (c) **1b**, and (d) **2b** and (e−h) ^{1}H DOSY spectra of (e) **1a**, (f) **2a**, (g) **1b**, and (h) **2b** (BF_4 salts of **2**, DMSO-d_6, 500 MHz, 300 K).

−10.4) was assembled upon heating of a 2:1 mixture of **1b** and $Pd(BF_4)_2$·4MeCN in DMSO-d_6 at 70 °C for 2.5 h. The ^{1}H NMR (Figure 1d) and DOSY (Figure 1h) spectra display the same characteristics as described above for sphere **2a**, indicating the formation of an $M_{12}L_{24}$ structure with uncoordinated pyridine rings on the exterior surface of the framework. This structure was again confirmed by CSI-TOF MS with the observation of a series of peaks for $[Pd_{12}\mathbf{1b}_{24}\cdot(BF_4)_{24} - nBF_4]^{n+}$ (n = 8−12).

Although it is likely that complex mixtures of metal−ligand oligomers formed during the early stages, the highly symmetric $M_{12}L_{24}$ structures **2a** and **2b** in which only the terminal pyridyl groups of the ligand are coordinated were the exclusive self-assembly products. These structures are remarkably stable because of the cooperation of 48 weak Pd^{2+}−pyridine interactions and therefore are the most thermodynamically stable species.[18,19] In the self-assembly of **2a**, coordination at the central pyridine is additionally sterically hindered as well as electronically disfavored because the central nitrogen atom has a smaller partial charge (−0.397) than the terminal pyridyl moieties (−0.446) (NBO/B3LYP calculation; see the Supporting Information). As a result, two $M_{12}L_{24}$ spheres containing exactly 24 free pyridine sites available for further coordination on their interior or exterior surfaces could be successfully assembled from Pd^{2+} ions and the tridentate tris(pyridine) ligands **1a** and **1b**.

Single crystals of the BF_4 salts of spheres **2a** and **2b** suitable for synchrotron X-ray crystallography were obtained by slow diffusion of 1,2-dimethoxyethane and chloroform vapor, respectively, into DMSO-d_6 solutions of the complexes. In both cases, structural refinement confirmed the $M_{12}L_{24}$ structure and the uncoordinated pyridine moieties lining the interior or exterior of the framework (Figure 2).

Non-convalent functionalization of the spherical framework was first examined for **2a**. All attempts to coordinate secondary metal ions to **2a** in DMSO-d_6 or CD_3CN were unsuccessful. Since DMSO and acetonitrile are strongly coordinating and as solvents are present in very large excess, we speculated that preferential coordination of the solvent to the secondary metal ion prevented its interaction with the pyridine moieties contained within the spherical framework.

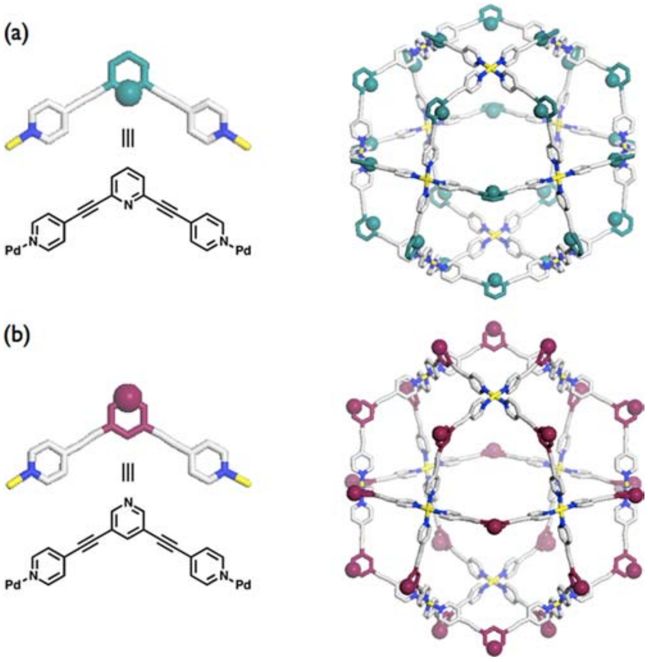


Figure 2. X-ray crystal structures of the BF_4 salts of (a) **2a** and (b) **2b**, highlighting the free nitrogen atoms on the central pyridine rings. H atoms, counterions, and solvent molecules have been omitted for clarity.

Therefore, the weakly coordinating[20] solvent nitromethane-d_3 (CD_3NO_2) was examined for the self-assembly of **2a** from ligand **1a** and $Pd(BF_4)_2$·4MeCN.[21] When $AgBF_4$ was added to a solution of **2a** in CD_3NO_2 (10 mM ligand concentration, corresponding to a sphere concentration of 0.42 mM), the proton signals of the central pyridine ring were shifted significantly downfield [at equilibrium, $\Delta\delta(H^c)$ = +0.25 ppm and $\Delta\delta(H^d)$ = +0.25 ppm] while the terminal pyridyl signals were shifted only slightly [at equilibrium, $\Delta\delta(H^a)$ = +0.06 ppm and $\Delta\delta(H^b)$ = +0.06 ppm] (Figure 3). The weaker coordination of Ag^+ to the central pyridine compared with the coordination of Pd^{2+} to the terminal pyridyl moieties is indicated by the averaging of the free and coordinated signals on the NMR time scale as a result of the fast equilibrium between the two species. ^{1}H DOSY measurements (see the Supporting Information) confirmed that the spherical structure was retained upon Ag^+ coordination. The

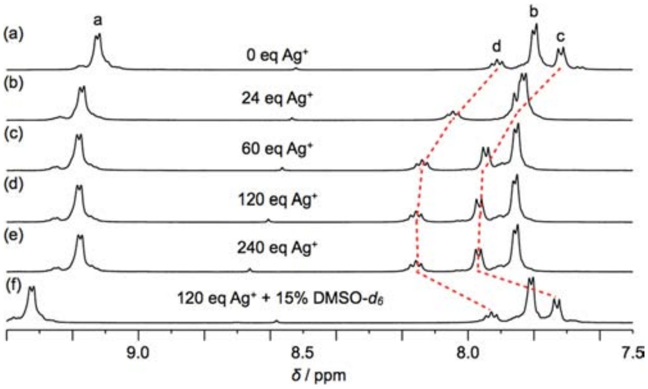


Figure 3. ^{1}H NMR spectra of (a−e) solutions of **2a** and various amounts of $AgBF_4$ (CD_3NO_2, 500 MHz, 300 K) and (f) the solution of **2a** containing 120 equiv of $AgBF_4$ after addition of 15% (v/v) DMSO-d_6. The H^a proton signal of empty sphere **2a** was also shifted downfield in this solvent mixture.

use of the weakly coordinating solvent CD_3NO_2 was essential for coordination of the secondary metal ion. The addition of 15% (v/v) DMSO-d_6 to the 0.42 mM solution of **2a** containing 120 equiv of $AgBF_4$ (relative to the sphere concentration) resulted in the immediate return of the proton signals of the central pyridine ring to the positions observed for the free $M_{12}L_{24}$ sphere (Figure 3f).

Single crystals of **2a**·24Ag^+ were grown by vapor diffusion of 1,2-dimethoxyethane into a mixture of **2a** and 240 equiv of $AgBF_4$ (relative to the sphere concentration) in CD_3NO_2. The X-ray structure (Figure 4) clearly shows the 24 Ag^+ ions coordinated to the central pyridine rings within the spherical framework structure. The occupancy of each Ag^+ ion is around 80%.

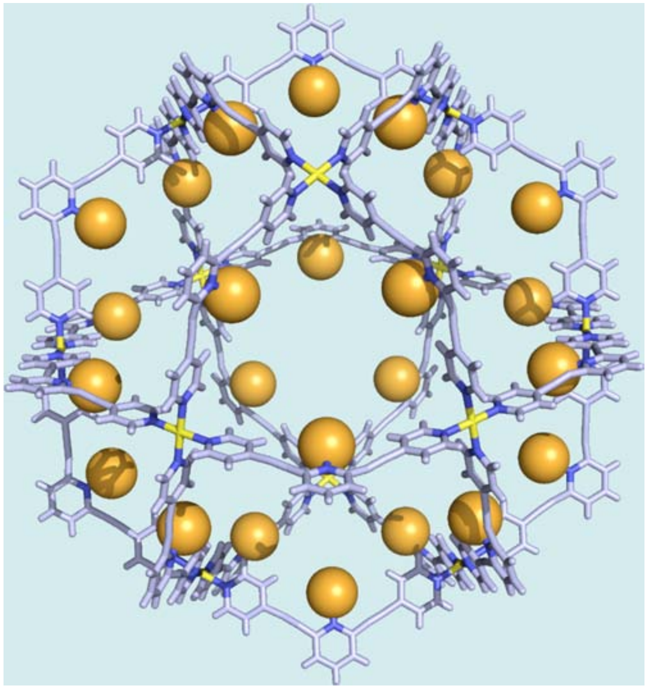


Figure 4. X-ray crystal structure of **2a** with 24 Ag^+ ions coordinated to the central pyridine rings on the interior surface of the framework. Counterions and solvent molecules have been omitted for clarity.

Similar coordination of Ag^+ ions at the exterior of **2b** was also examined (see the Supporting Information). Sphere **2b** did not form as a single product in pure CD_3NO_2,[21] so the experiments were conducted in a 19:1 mixture of CD_3NO_2 and DMSO-d_6. In this case, addition of 240 equiv of $AgBF_4$ resulted in immediate precipitation of an off-white solid. We propose that this occurred as a result of the formation of an insoluble network of spheres **2b** bridged by the linear coordination of Ag^+ to the central pyridine rings.

In summary, we have demonstrated the self-assembly of $M_{12}L_{24}$ spherical complexes containing 24 free pyridine binding sites on their interior or exterior surfaces. Through coordination of metal ions to these binding sites, we have developed a non-covalent method for the functionalization of $M_{12}L_{24}$ spherical complexes. We envisage that varying the secondary metal ion or non-covalent interactions will allow the synthesis of a variety of endo- and exohedrally functionalized spherical complexes from a single spherical platform, thereby simplifying the functionalization and application of this class of self-assembled complexes.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Experimental details, characterization data, and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

mfujita@appchem.t.u-tokyo.ac.jp

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This research was supported by the Swiss National Science Foundation Fellowship for Prospective Researchers, the JSPS Postdoctoral Fellowship (Short-Term) for North American and European Researchers, and also in part by KAKENHI (Grant-in-Aid for Scientific Research on Innovative Areas: "Fusion Materials") from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and a Grant-in-Aid for Young Scientists (A) from MEXT. Synchrotron X-ray diffraction studies were performed at SPring-8 and KEK.

■ REFERENCES

(1) Chakrabarty, R.; Mukherjee, P. S.; Stang, P. J. *Chem. Rev.* **2011**, *111*, 6810.

(2) Vriezema, D. M.; Comellas Aragonès, M.; Elemans, J. A. A. W.; Cornelissen, J. J. L. M.; Rowan, A. E.; Nolte, R. J. M. *Chem. Rev.* **2005**, *105*, 1445.

(3) Yoshizawa, M.; Klosterman, J. K.; Fujita, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 3418.

(4) Hof, F.; Craig, S. L.; Nuckolls, C.; Rebek, J., Jr. *Angew. Chem., Int. Ed.* **2002**, *41*, 1488.

(5) Rebek, J., Jr. *Angew. Chem., Int. Ed.* **2005**, *44*, 2068.

(6) Pluth, M. D.; Bergman, R. G.; Raymond, K. N. *Acc. Chem. Res.* **2009**, *42*, 1650.

(7) Fiedler, D.; Leung, D. H.; Bergman, R. G.; Raymond, K. N. *Acc. Chem. Res.* **2005**, *38*, 349.

(8) Tominaga, M.; Suzuki, K.; Kawano, M.; Kusukawa, T.; Ozeki, T.; Sakamoto, S.; Yamaguchi, K.; Fujita, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 5621.

(9) Sun, Q. F.; Iwasa, J.; Ogawa, D.; Ishido, Y.; Sato, S.; Ozeki, T.; Sei, Y.; Yamaguchi, K.; Fujita, M. *Science* **2010**, *328*, 1144.

(10) Furukawa, H.; Kim, J.; Plass, K. E.; Yaghi, O. M. *J. Am. Chem. Soc.* **2006**, *128*, 8398.

(11) Perry, J. J.; Kravtsov, V. C.; Zaworotko, M. J.; Larsen, R. W. *Cryst. Growth Des.* **2011**, *11*, 3183.

(12) Volkmer, D.; Du Chesne, A.; Kurth, D. G.; Schnablegger, H.; Lehmann, P.; Koop, M. J.; Müller, A. *J. Am. Chem. Soc.* **2000**, *122*, 1995.

(13) Zheng, Y.-R.; Wang, M.; Kobayashi, S.; Stang, P. J. *Tetrahedron Lett.* **2011**, *52*, 2188.

(14) Yamamoto, T.; Arif, A. M.; Stang, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 12309.

(15) Sato, S.; Iida, J.; Suzuki, K.; Kawano, M.; Ozeki, T.; Fujita, M. *Science* **2006**, *313*, 1273.

(16) Murase, T.; Sato, S.; Fujita, M. *Angew. Chem., Int. Ed.* **2007**, *46*, 1083.

(17) Suzuki, K.; Takao, K.; Sato, S.; Fujita, M. *J. Am. Chem. Soc.* **2010**, *132*, 2544.

(18) Sato, S.; Ishido, Y.; Fujita, M. *J. Am. Chem. Soc.* **2009**, *131*, 6064.

(19) Sun, Q.-F.; Sato, S.; Fujita, M. *Nat. Chem.* **2012**, *4*, 330.

(20) Díaz-Torres, R.; Alvarez, S. *Dalton Trans.* **2011**, *40*, 10742.

(21) See the Supporting Information for the preparation of **2a** and **2b** in CD_3NO_2.