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Self-assembled Inverse Dendrimer

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Bent bridging ligands appending dendrons (G-1, G-2, and G-3) at their concaves are complexed with Pd(II) ions to self-assemble into $M_{12}L_{24}$ spherical shells confining inversely branched dendrimers. Their structures were fully characterized by NMR, CSI-TOF-MS, and AFM.

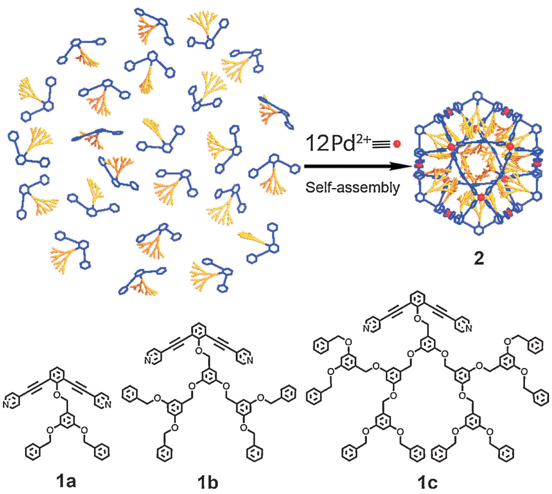
Dendrimers are structurally well-defined, hyperbranched polymers with branches stretching out from the core to the outside.[1–3] They are typically synthesized by divergent[4] or convergent[5] covalent synthesis, or sometimes, by noncovalent self-assembly methods, where the hyperbranched dendrons are used as building blocks. If the branches are anchored onto the inner wall of a capsular molecule with a defined structure to stretch out from the shell to the core, the product is a new type of dendrimer that can be called an "inverse dendrimer."[6] Previously, we have shown that giant hollow coordination $M_{12}L_{24}$ spheres with a precise chemical structure and uniform diameter are spontaneously self-assembled by simply mixing 12 Pd(II) ions and 24 bent bidentate ligands.[7,8] Here, we report that by appending the dendrons at the concave of the bent ligands, inverse dendrimers with controlled interior density are efficiently prepared, demonstrating the high potential of metal-directed self-assembly to create a new class of nanosized molecular materials (Scheme 1).

Three generations of Frechet-type oligo(benzyl ether) dendrons were attached at the concave of bent bipyridyl ligands before complexation. The ligands were synthesized in two steps with reasonable yields: the dendrons were connected to 2,6-dibromophenol by Williamson ether synthesis, and then two 4-pyridylethynyl groups were introduced by Sonogashira coupling.[9]

When ligand **1b** (10 µmol) was treated with $Pd(BF_4)_2$ (5 µmol) in CD_3CN (1.0 mL) at 50 °C for 3 h, the quantitative self-assembly of a single and highly symmetric product was confirmed by ^1H NMR (Figure 1). From this NMR and MS analysis (as discussed later), the structure of the product was deduced to be a spherical inverse dendrimer **2b**. The downfield shift ($\Delta\delta = 0.34$) of the α-proton on the pyridyl group is characteristic for the coordination on Pd(II) ions. Meanwhile, all the other signals for the dendritic substituents are found to be clearly upfield shifted. The upfield shift is presumably due to the crowded packing of benzyl groups inside the sphere and, in part, the magnetic shielding from the $M_{12}L_{24}$ shell.

The $M_{12}L_{24}$ composition of sphere **2b** was established by CSI-TOF mass spectrum in terms of exact mass, multivalency, and high-resolution isotope patterns. As shown in Figure 2, prominent peak series corresponding to $[\mathbf{2b} - (BF_4^-)_n]^{n+}$ ($n = 7$–16) were observed, from which the molecular weight was calculated to be 27917.08 Da, confirming the $M_{12}L_{24}$ component. The high-resolution mass spectrum showed the highest peak to be in a 12^+ charged state.

In the same way, spheres **2a** and **2c** were self-assembled and characterized by ^1H NMR and MS. It is worth mentioning that the molecular weight of sphere **2c** amounts to 48292.90, yet a series of $[\mathbf{2c} - (BF_4^-)_n]^{n+}$ ($n = 9$–17) peaks were clearly observed. Because of the huge molecular weight, highly resolved isotope patterns were not observed (Figure S18[9]).



Scheme 1. Schematic representation of the self-assembly of inverse dendrimers and the structures of three generations of ligands **1a**–**1c**.

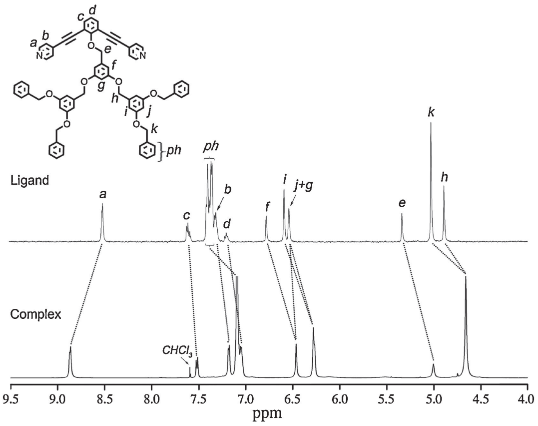


Figure 1. ^1H NMR spectra of ligand **1b** (500 MHz, CD_3CN, 300 K) and complex **2b** (500 MHz, CD_3CN, 300 K).

To estimate the molecular size, DOSY (diffusion ordered spectroscopy) measurements were performed. Obtained similar diffusion coefficients $D = 2.57 \times 10^{-10}\,m^2\,s^{-1}$ for spheres **2a** and **2b** and calibrated $D = 2.53 \times 10^{-10}\,m^2\,s^{-1}$ for sphere **2c** in CD_3CN (see SI[9]) proved that all the spheres are almost the same size, but sphere **2c** is slightly larger than spheres **2a** and **2b**. The characteristic behavior for sphere **2c** was also observed in the ^1H NMR spectrum, which showed severely broadened signals

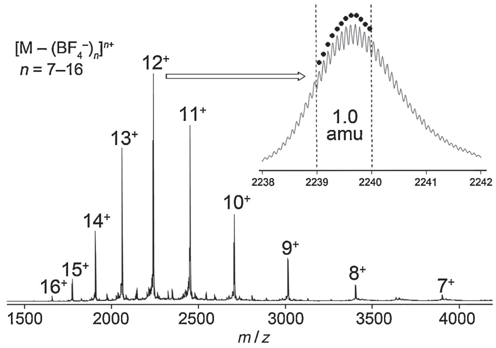


Figure 2. CSI-TOF mass spectrum of sphere **2b** with an inset showing the isotope pattern for the 12^+ charged peak.

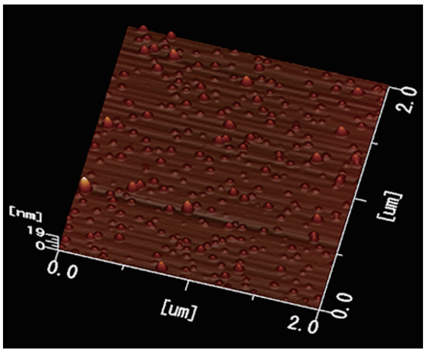


Figure 3. AFM image of sphere **2b** on mica.

(Figures S9–S12[9–11]). The apparently different line width and slightly small *D* value of **2c** can be understood by the optimized structure of these inverse dendrimers (Figure S20[9,10]). Taking the furthest Pd···Pd distance as the diameter of the hollow shell, the occupancies of the dendron segments are calculated to be 31%, 76%, and 169% for **2a**, **2b**, and **2c**, respectively (Materials Studio 4.4). This suggests that some of the branches in **2c** "break" out of the spherical "prison" through the square or triangle "windows" of the framework. The over-staffed nature of the G-3 dendrimer, which makes benzyl groups packed in high density, together with the large molecular weight (48292.90 Da for $[Pd_{12}(C_{125}H_{102}N_2O_{15})_{24}]^{24+}\cdot 24BF_4^-$), explains the line broadness and a slightly larger molecular diameter.

The solid-state structure of **2b** on a surface was observed by atomic force microscopy (AFM). A representative image of the surface pattern is shown in Figure 3, where most of the inverse dendrimers maintained their spherical shapes. Height of the inverse dendrimer was roughly 5 nm, consistant with the diameter of the $M_{12}L_{24}$ framework.

Our reverse dendrimers are characteristic compared with "normal" ones in the following aspects: (1) Whereas the segment density of common dendrimers gradually increases from the core to the outer sphere, that of the inverse dendrimers drastically increases from the outer to inner sphere and then drops to nearly zero at the core (Figure 4); (2) Defined by the rigid $M_{12}L_{24}$ shell, the size, shape, and molecular weight are perfectly uniform; (3) The precursor dendrons are summed up through the self-assembly the $M_{12}L_{24}$ shell.

In summary, the present study describes the self-assembly of newly defined inverse dendrimers by taking the advantage of an around 5 nm-sized $M_{12}L_{24}$ spherical rigid framework. The enlargement of the spherical framework itself is in progress, and we envision that the inverse dendritic architecture can be applied for material syntheses of uniform-sized nanoparticles which have controlled internal density.

Figure 4. Cartoon presentation for the segment density in the normal (left) and inverse (right) dendrimers.

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9 Supporting Information is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem-lett/index.html.

10 All the behaviors of **2a**–**2c** in CSI-MS, ^{1}H NMR, DOSY, and AFM were consistent with those of $M_{12}L_{24}$ spherical complexes whose shell frameworks were unambiguously determined by X-ray crystallography. A remarkable kinetic stabilization of the resultant $M_{12}L_{24}$ spherical structures has been discussed (where the ligand exchange is 10^6 times slower than that in mononuclear Pd(II)–pyridine complex). Also, mathematical constraint allows only five structures for M_nL_{2n} spheres ($n = 6$, 12, 24, 30, and 60), and the *n* values critically change when the structural parameters of the ligand are modulated, thus forming a unique single structure rather than a mixture with different *n* values. Based on these previous findings, we confirmed the stable, unique formation of **2a**–**2c**.

11 Because of this broadening, further studies may be required to fully characterize the structure **2c**.