Supporting information:

Remarkable Stabilization of $M_{12}L_{24}$ Spherical Frameworks through the Cooperation of 48 Pd(II)-Pyridine Interactions

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General

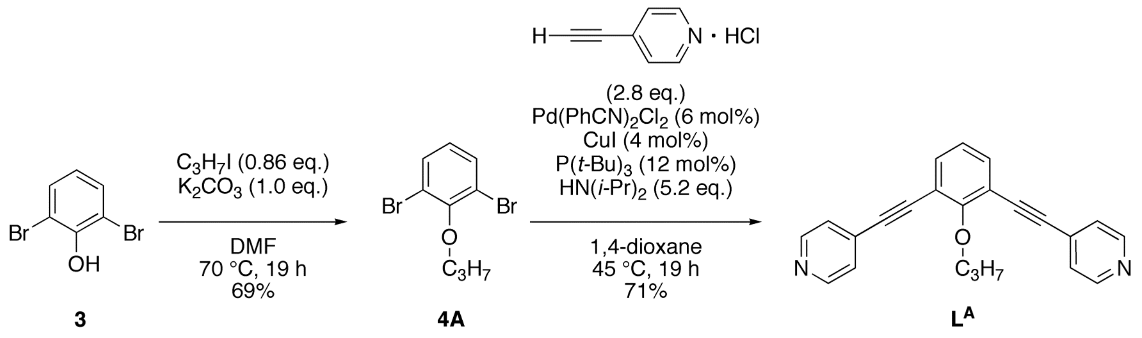
^{1}H, ^{13}C NMR, and 2D NMR spectra were obtained on a Bruker DRX-500 spectrometer equipped with a 5 mm BBO Z-gradient probe, on a Bruker AV-500 spectrometer equipped with the 5 mm CP-TCI cryoprobe, and on a JEOL AL-300 spectrometer equipped with a 5 mm TH5 probe. IR spectra were obtained on a Varian FTS-2000 Scimitar spectrometer as a KBr pellet sample and on a Varian FTS-7000 spectrometer as a thin film between CaF_2 plates. Melting points were determined on a Yanaco MP-500V melting-point apparatus. GC-MS spectra were obtained on an Agilent 6890 GC with an Agilent 5973 inert spectrometer equipped with an EI source. CSI-MS (cold-spray ionization mass spectrometry) spectra were obtained on a four-sector (BE/BE) tandem mass spectrometer (JMS-700C, JEOL) equipped with a CSI source. Gel permeation chromatography (GPC) was carried out using a LC-908 equipped with RI and UV detectors using JAIGEL 1H and 2H columns eluted by chloroform. Elemental analyses for carbon, hydrogen, and nitrogen were performed on a Yanaco MT-6.

Solvents and reagents were purchased from TCI Co., Ltd., WAKO Pure Chemical Industries Ltd., and Sigma-Aldrich Co.

Procedure

- Syntheses and physical properties of ligands **L**^{A} and **L**^{B}.

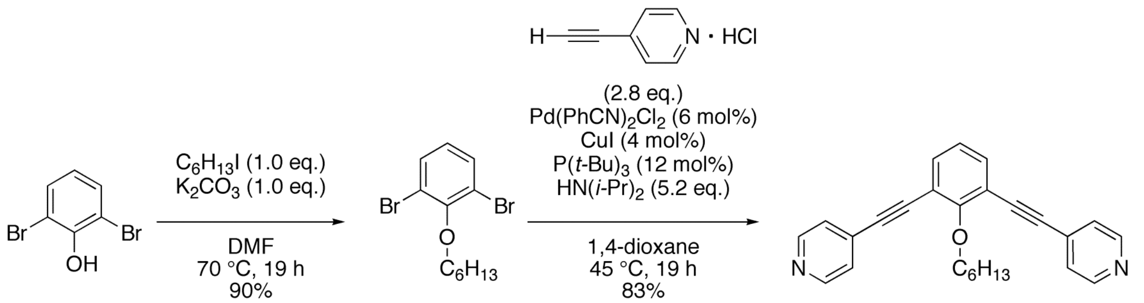
Ligand L^{A} was synthesized as follows:



2,6-Dibromophenyl propyl ether (4A): A mixture of 2,6-dibromophenol **3** (1.02 mg, 4.04 mmol), potassium carbonate (555 mg, 4.02 mmol), and 1-iodopropane (340 μL, 3.48 mmol) was stirred in dimethylformamide (20 mL) at 70 °C for 19 h under argon atmosphere. The reaction mixture was evaporated under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane:ethyl acetate = 100:1) to give the title compound as colorless oil (703 mg, 2.39 mmol) in 69% yield. GC-MS calcd for $C_9H_{10}Br_2O$ ($[M]^+$) 294, found 294; ^{1}H NMR (500 MHz, $CDCl_3$, 300 K) δ 7.49 (d, J = 8.0 Hz, 2H), 6.84 (t, J = 8.0 Hz, 1H), 3.98 (t, J = 6.6 Hz, 2H), 1.94-1.87 (m, 2H), 1.10 (t, J = 7.4 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$, 300 K) δ 153.57 (Cq), 132.71 (CH), 126.03 (CH), 118.59 (Cq), 75.01 (CH_2), 23.39 (CH_2), 10.49 (CH_3); IR (CaF_2, cm^{-1}) 2965, 2937, 2876, 1554, 1440, 1384, 1248, 1197, 1070, 991; Elemental Analysis Calcd for $C_9H_{10}Br_2O$: C, 36.77; H, 3.43. Found: C, 36.85; H, 3.45.

2,6-Bis(4-pyridylethynyl)phenyl propyl ether (L^{A}): Tri-*t*-butylphosphine (560 μL, 0.225 mmol; 10% solution in hexane) and diisopropylamine (1.38 mL, 9.76 mmol) were added to a mixture of compound **4A** (541 mg, 1.84 mmol), 4-ethynylpyridine hydrochloride (730 mg, 5.23 mmol), Pd(PhCN)$_2$Cl$_2$ (45.1 mg, 0.115 mmol), and Copper(I) iodide (16.5 mg, 0.0866 mmol) in 1,4-dioxane (8 mL), and the mixture was stirred at 45 °C for 19 h under argon atmosphere. The reaction mixture was diluted with ethyl acetate and filtered. The filtrate was washed with water (30 mL), and the aqueous layer was extracted with ethyl acetate. The combined organic layer was washed with 10% aqueous ethylenediamine (30 mL), water (30 mL × 2), and saturated brine (30 mL), successively. The organic layer was dried over anhydrous sodium sulfate and evaporated under reduced pressure, and the residue was purified by column chromatography on silica gel (chloroform:methanol = 50:1) and GPC to give the title compound as brown powder (406 mg, 1.20 mmol) in 71% yield. m.p. 68-69 °C; GC-MS calcd for $C_{23}H_{18}N_2O$ ($[M]^+$) 338, found 338; ^1H NMR (500 MHz, $CDCl_3$, 300 K) δ 8.63 (dd, J = 1.6, 4.5 Hz, 4H), 7.54 (d, J = 7.7 Hz, 2H), 7.38 (dd, J = 1.6, 4.5 Hz, 4H), 7.11 (t, J = 7.7 Hz, 1H), 4.29 (t, J = 6.4 Hz, 2H), 1.96-1.89 (m, 2H), 1.14 (t, J = 7.4 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$, 300 K) δ 161.95 (Cq), 149.97 (CH), 134.75 (CH), 131.34 (Cq), 125.44 (CH), 123.62 (CH), 116.98 (Cq), 91.18 (Cq), 89.92 (Cq), 76.53 (CH_2), 23.89 (CH_2), 10.91 (CH_3); IR (KBr, cm^{-1}) 3022, 2965, 2936, 2872, 2217, 1593, 1538, 1489, 1441, 1400, 1233, 1072, 989, 955, 817, 791, 761, 738; Elemental Analysis Calcd for $C_{23}H_{18}N_2O$: C, 81.63; H, 5.36; N, 8.28. Found: C, 81.36; H, 5.53; N, 8.10.

Ligand L^B was synthesized as follows:



3 **4B** $\mathbf{L^B}$

2,6-Dibromophenyl hexyl ether (4B): A mixture of 2,6-dibromophenol **3** (1.01 mg, 4.03 mmol), potassium carbonate (556 mg, 4.02 mmol), and 1-iodohexane (600 μL, 4.07 mmol) was stirred in dimethylformamide (20 mL) at 70 °C for 19 h under argon atmosphere. The reaction mixture was evaporated under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane:ethyl acetate = 100:1) to give the title compound as colorless oil (1.21 g, 3.61 mmol) in 90% yield; GC-MS calcd for $C_9H_{10}Br_2O$ ($[M]^+$) 336, found 336; ^1H NMR (500 MHz, $CDCl_3$, 300 K) δ 7.48 (d, J = 8.0 Hz, 2H), 6.82 (t, J = 8.0 Hz, 1H), 4.01 (t, J = 6.6 Hz, 2H), 1.90-1.85 (m, 2H), 1.57-1.51 (m, 2H), 1.39-1.36 (m, 4H), 0.92 (t, J = 7.4 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$, 300 K) δ 153.73 (Cq), 132.65 (CH), 125.97 (CH), 118.57 (Cq), 73.51 (CH_2), 31.66 (CH_2), 30.01 (CH_2), 25.56 (CH_2), 22.63 (CH_2), 14.08 (CH_3); IR (CaF_2, cm^{-1}) 2954, 2931, 2871, 1555, 1442, 1380, 1247, 1197, 1071, 995; Elemental Analysis Calcd for $C_{12}H_{16}Br_2O$: C, 42.89; H, 4.80. Found: C, 42.65; H, 4.64.

2,6-Bis(4-pyridylethynyl)phenyl hexyl ether (L^B): Tri-*t*-butylphosphine (560 μL, 0.225 mmol; 10% solution in hexane) and diisopropylamine (1.40 mL, 9.91 mmol) were added to a mixture of compound **4B** (636 mg, 1.89 mmol), 4-ethynylpyridine hydrochloride (741 mg, 5.31 mmol), $Pd(PhCN)_2Cl_2$ (45.2 mg, 0.115 mmol), and Copper(I) iodide (14.7 mg, 0.0772 mmol) in 1,4-dioxane (10 mL), and the mixture was stirred at 45 °C for 19 h under argon atmosphere. The reaction mixture was diluted with ethyl acetate and filtered. The filtrate was washed with water (30mL × 3), and the aqueous layer was extracted with ethyl acetate. The combined organic layer was washed with 10% aqueous ethylenediamine (30mL × 2), water (30mL × 3), and saturated brine (30 mL), successively. The organic layer was dried over anhydrous sodium sulfate and evaporated under reduced pressure, and the residue was purified by column chromatography on silica gel (chloroform:methanol = 50:1) and GPC to give the title compound as brown oil (595 mg, 1.56 mmol) in 83% yield. GC-MS calcd for $C_{23}H_{18}N_2O$ ($[M]^+$) 380, found 380; ^{1}H NMR (300 MHz, $CDCl_3$, 293 K) δ 8.63 (d, J = 5.7 Hz, 4H), 7.54 (d, J = 7.8 Hz, 2H), 7.39 (dd, J = 1.5, 4.5 Hz, 4H), 7.11 (t, J = 7.8 Hz, 1H), 4.32 (t, J = 6.3 Hz, 2H), 1.93-1.84 (m, 2H), 1.63-1.53 (m, 2H), 1.36-1.27 (m, 4H), 0.84 (t, J = 7.0 Hz, 3H); ^{13}C NMR (125 MHz, DMSO-d_6, 300 K) δ 161.30 (Cq), 150.05 (CH), 134.90 (CH), 129.97 (Cq), 125.18 (CH), 124.24 (CH), 116.07 (Cq), 90.99 (Cq), 89.33 (Cq), 74.55 (CH_2), 31.06 (CH_2), 29.88 (CH_2), 25.41 (CH_2), 22.01 (CH_2), 13.78 (CH_3); IR (CaF_2, cm^{-1}) 3072, 3038, 2954, 2930, 2870, 2217, 1594, 1538, 1490, 1442, 1405, 1380, 1236, 1077, 990, 969; Elemental Analysis Calcd for $C_{26}H_{24}N_2O$:C, 82.07; H, 6.36; N, 7.36. Found: C, 81.84; H, 6.55; N, 7.11.

- Syntheses and physical properties of spheres **1** and **2**.

Synthesis of sphere 1 (NO_3^- salt, DMSO-d_6): Compound **L**^{A} (3.38 mg, 10.0 μmol) was treated with $Pd(NO_3)_2$ (1.38 mg, 6.00 μmol) in DMSO (0.70 mL) at 70 °C for 5 h. The quantitative formation of **1** was confirmed by ^1H NMR; ^1H NMR (500 MHz, DMSO-d_6, 300 K) δ 9.23 (br, 96H), 7.78 (br, 96H), 7.69 (br, 48H), 7.27 (br, 24H), 4.24 (br, 48H), 1.83 (br, 48H), 1.07 (br, 72H); ^{13}C NMR (125 MHz, DMSO-d_6, 300 K) δ 162.25 (Cq), 151.15 (CH), 136.15 (CH), 134.07 (Cq), 128.29 (CH), 124.41 (CH), 115.00 (Cq), 93.93 (Cq), 89.59 (Cq), 76.59 (CH_2), 23.19 (CH_2), 10.58 (CH_3); Diffusion coefficient $D = (4.0 \pm 0.1) \times 10^{-11}$ m^2s^{-1} determined by ^1H nucleus detection.

Synthesis of sphere 1 ($CF_3SO_3^-$ salt, CH_3CN): Compound **L**^{A} (3.38 mg, 10.0 μmol) was treated with $Pd(CF_3SO_3)_2$ (2.83 mg, 7.00 μmol) in CH_3CN (5.00 mL) at 50 °C for 5 h. The solution was separated by centrifugation and was analyzed by mass spectrometry. CSI-MS ($CF_3SO_3^-$ salt, CH_3CN) calcd for $[M - 7(OTf^-)]^{7+}$ 1704.6, found 1704.7; calcd for $[M - 8(OTf^-)]^{8+}$ 1472.9, found 1473.0; calcd for $[M - 9(OTf^-)]^{9+}$ 1292.7, found 1292.7; calcd for $[M - 10(OTf^-)]^{10+}$ 1148.6, found 1148.6; calcd for $[M - 11(OTf^-)]^{11+}$ 1030.6, found 1030.6; calcd for $[M - 12(OTf^-)]^{12+}$ 932.3, found 932.3; calcd for $[M - 13(OTf^-)]^{13+}$ 849.1, found 849.2.

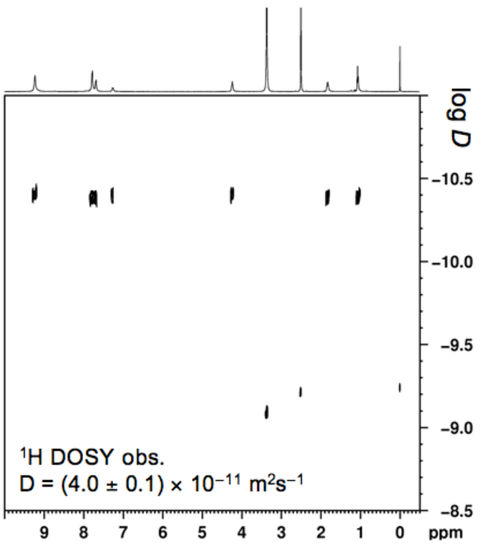


Fig. S1. DOSY spectrum of sphere **1** (500 MHz, DMSO-d_6, 300 K).

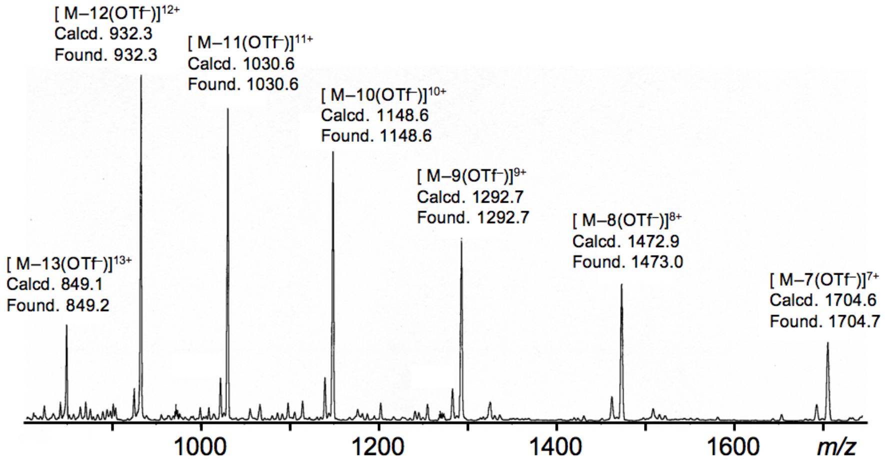


Fig. S2. CSI-MS spectrum of sphere **1** ($CF_3SO_3^-$ salt, CH_3CN).

Synthesis of sphere 2 (NO_3^- salt, DMSO-d_6): Compound $\mathbf{L^B}$ (4.27 mg, 11.2 μmol) was treated with $Pd(NO_3)_2$ (1.55 mg, 6.74 μmol) in DMSO (0.70 mL) at 70 °C for 5 h. The quantitative formation of **2** was confirmed by ^1H NMR; ^1H NMR (500 MHz, DMSO-d_6, 300 K) δ 9.26 (br, 96H), 7.79 (br, 96H), 7.67 (br, 48H), 7.25 (br, 24H), 4.24 (br, 48H), 1.74 (br, 48H), 1.43 (br, 48H), 1.19 (br, 48H), 1.11 (br, 48H), 0.61 (br, 72H); ^{13}C NMR (125 MHz, DMSO-d_6, 300 K) δ 162.32 (Cq), 151.16 (CH), 136.23 (CH), 134.20 (Cq), 128.41 (CH), 124.50 (CH), 115.02 (Cq), 94.05 (Cq), 89.65 (Cq), 75.22 (CH_2), 31.06 (CH_2), 29.85 (CH_2), 25.32 (CH_2), 22.00 (CH_2), 13.68 (CH_3); Diffusion coefficient $D = (4.0 \pm 0.3) \times 10^{-11}$ m^2s^{-1} determined by ^1H nucleus detection.

Synthesis of sphere 2 ($CF_3SO_3^-$ salt, CH_3CN): Compound $\mathbf{L^B}$ (3.80 mg, 10.0 μmol) was treated with $Pd(CF_3SO_3)_2$ (2.83 mg, 7.00 μmol) in CH_3CN (5.00 mL) at 50 °C for 5 h. The solution was separated by centrifugation and was analyzed by mass spectrometry. CSI-MS ($CF_3SO_3^-$ salt, CH_3CN) calcd for $[M - 8(OTf^-)]^{8+}$ 1599.2, found 1599.4; calcd for $[M - 9(OTf^-)]^{9+}$ 1405.0, found 1405.0; calcd for $[M - 10(OTf^-)]^{10+}$ 1249.6, found 1249.7; calcd for $[M - 11(OTf^-)]^{11+}$ 1122.3, found 1122.5; calcd for $[M - 12(OTf^-)]^{12+}$ 1016.4, found 1016.6; calcd for $[M - 13(OTf^-)]^{13+}$ 926.8, found 926.9; calcd for $[M - 14(OTf^-)]^{14+}$ 849.9, found 850.1.

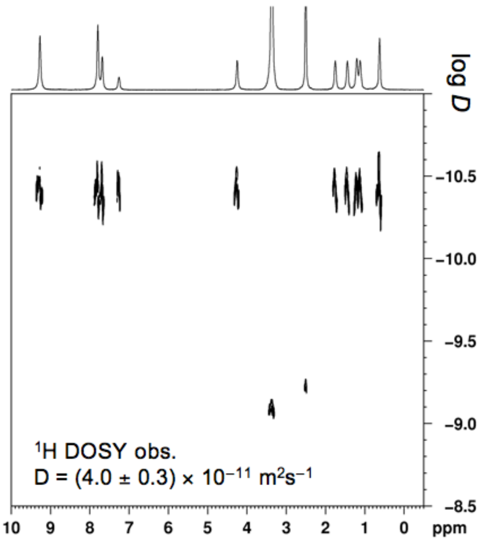


Fig. S3. DOSY spectrum of sphere **2** (500 MHz, DMSO-d_6, 300 K).

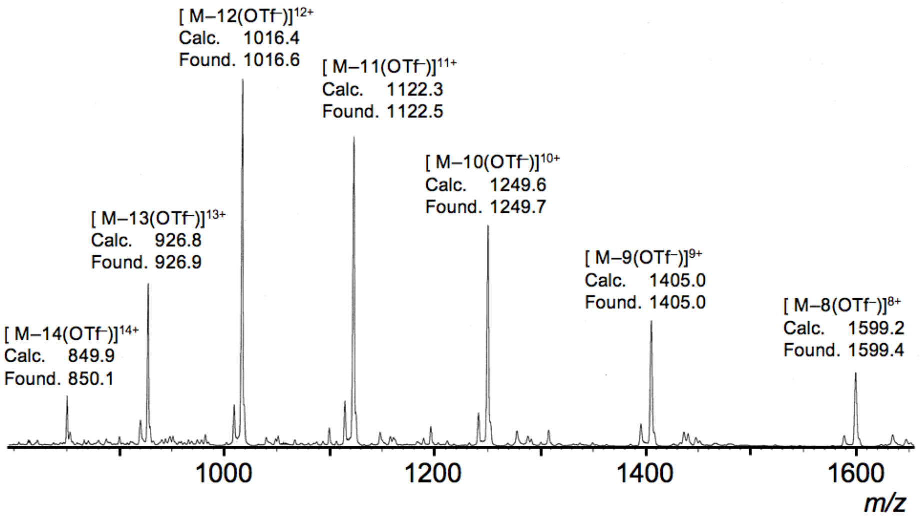


Fig. S4. CSI-MS spectrum of sphere **2** ($CF_3SO_3^-$ salt, CH_3CN).

・Quantification of spheres **1** and **2**.

A solution of TSP-*d*$_4$ (3-(trimethylsilyl) propionic-2,2,3,3-*d*$_4$ acid, sodium salt) in D_2O was sealed in a separate tube <internal/outer diameter = 1.5 mm/2.5 mm>. The separate tube was put in a standard 5 mm NMR tube. A solution of sphere **1** in CH_3CN (370 μL) was placed in the outer NMR tube (Fig. S5). The solution was measured using quantitative 1D ^{1}H NMR with WATERGATE (WATER suppression by Gradient-Tailored Excitation) pulse program[1] and with relaxation delay of 60 s. The spectra were analyzed based on integration values of signals for spherical complex and internal standard TSP-*d*$_4$. By comparing the integration value of **1** with the calibrated value of TSP-*d*$_4$ as described below, the concentration of **1** was obtained.

Integration value of TSP-*d*$_4$ was calibrated with $CHBr_3$ solution. $CHBr_3$ (3.0 mM solution in DMSO-*d*$_6$) was placed in the outer NMR tube and analyzed using quantitative 1D ^{1}H NMR with WATERGATE. By comparing the integration value of TSP-*d*$_4$ to that of $CHBr_3$, integration value of TSP-*d*$_4$ was calibrated.

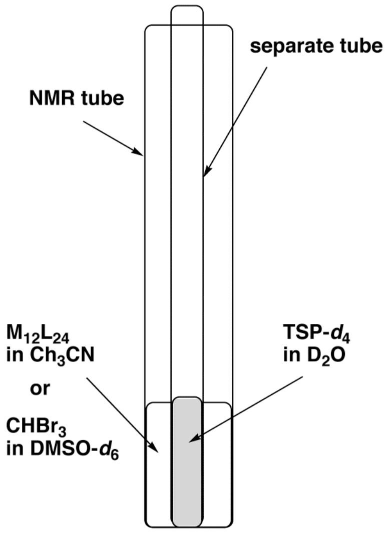
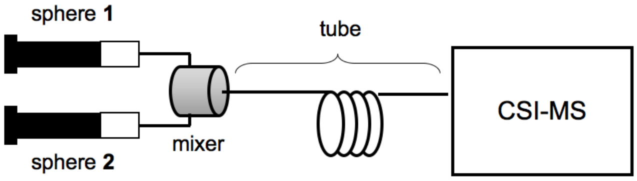


Fig. S5. The NMR tube with separate tube for internal standard calibration.

・Ionization efficiency of spheres **1** and **2**.

A mixture of sphere **1** (0.023 mM solution in CH_3CN) and sphere **2** (0.019 mM solution in CH_3CN) was analyzed by cold-spray ionization mass spectrometry at the various mixing ratios: **1**/**2** = 2:8, 4:6, 5:5, 6:4, 8:2 in volumetric ratio. The mixing ratio was controlled by the injection speed rates using two syringe-pumps and rapid mixing was achieved using continuous flow system with micro static mixer equipped with 25.0 μL cartridge (**Fig. S6a**). By the rapid mixing system, we observed mass spectra for **1** and **2**. Intensities of the peaks of **2** were plotted against the concentration ratio of **1** and **2** (**Fig. S6b**). The linear relationship between observed height and concentration revealed that the ionization efficiencies of **1** and **2** were equal.

(a)



(b)

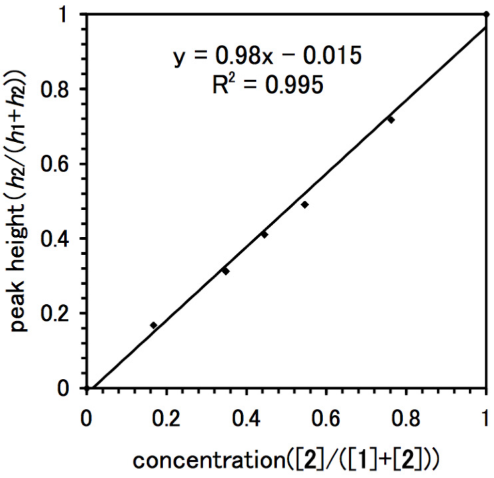


Fig. S6. (a) Rapid mixing system for CSI-MS measurement. (b) Plot of observed peak height ratio against concentration ratio of spherical complexes.

・Determination of ligand exchange rate of sphere **1** and sphere **2**.

A mixture of sphere **1** (0.025 mM solution in CH_3CN, 1.50 mL, 37.5 nmol) and sphere **2** (0.025 mM solution in CH_3CN, 1.50 mL, 37.5 nmol) was analyzed by cold-spray ionization mass spectrometry after a series of mixing times: 10 h, 20 h, 25 h, 35 h, 45 h, and 70 h. We confirmed that the ligand exchange did take place and, in addition to prominent peaks for **1** and **2**, new peaks gradually appeared which can be assigned as **3** and **4**. From the observed peak height ratios of **1** and **3**, concentrations of **1** were obtained. The values of (1/[**1**] – 1/[**1**]$_0$) were plotted against the mixing time **(Fig. S7)**. From this t vs. (1/[**1**] – 1/[**1**]$_0$) plots, the apparent exchange rate constant k_{obs} was estimated to be 2×10^{-2} [$M^{-1}s^{-1}$]. The calculated half-life of **1** was 20 days.

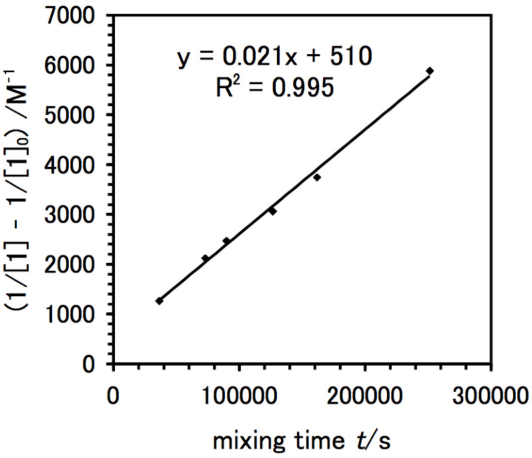


Fig. S7. Mixing time t vs. (1/[**1**] – 1/[**1**]$_0$) plots.

・Determination of ligand exchange rate of ligand **L**$^{\mathbf{A}}$ and sphere **2**.

A mixture of ligand **L**$^{\mathbf{A}}$ (1.7 mM solution in CH_3CN) and sphere **2** (0.031 mM solution in CH_3CN) was analyzed by cold-spray ionization mass spectrometry after a series of mixing times: 30 s, 60 s, 90 s, and 120 s. The mixing time was controlled by the tube length in the rapid mixing system **(Fig. S6a)**. We confirmed that the ligand exchange did take place and, in addition to prominent peaks for **2**, new peaks gradually appeared which can be assigned as **4**. From the observed peak height ratios of **2** and **4**, concentrations of **2** were obtained. The values of ln([**2**]/[**2**]$_0$) were plotted against the mixing time **(Fig. S8)**. From this t

vs. ln([**2**]/[**2**]$_0$) plots, the apparent exchange rate constant k_{obs} was estimated to be 5×10^{-4} [s^{-1}]. The calculated half-life of **2** was 23 minutes.

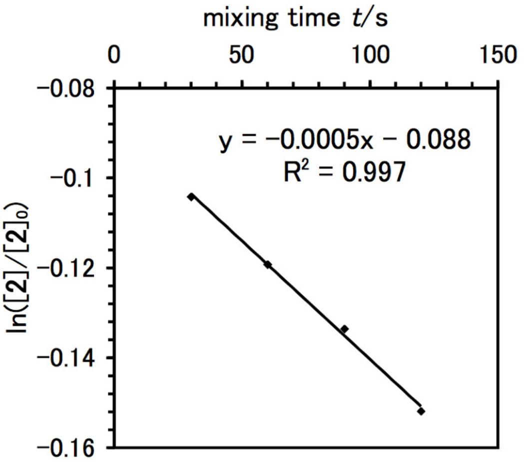


Fig. S8. Mixing time *t* vs. ln([**2**]/[**2**]$_0$) plots.

・Determination of ligand exchange rate of mononuclear model complex.

Tetrapyridyl palladium complex was synthesized as follows: Pyridine (3.16 mg, 40.0 μmol) was treated with $Pd(CF_3SO_3)_2$ (4.04 mg, 10.0 μmol) in CD_3CN (5.00 mL). The solution was separated by filtration and was analyzed by mass spectrometry. CSI-MS ($CF_3SO_3^-$ salt, CD_3CN) calcd for $[M - 2(OTf^-)]^{2+}$ 211.0, found 211.0; ^1H NMR (500 MHz, CD_3CN, 300 K) δ 8.75 (dd, *J* = 1.0, 6.0 Hz, 8H), 7.98 (tt, *J* = 1.5, 7.5 Hz, 4H), 7.53 (dd, *J* = 6.5, 7.5 Hz, 8H).

Ligand exchange reaction of $[Pd(py)_4]^{2+}$ was so fast that it couldn't be analyzed by mass spectrometry. Ligand exchange rate of $[Pd(py)_4]^{2+}$ was determined by a spin-saturation transfer experiment[2]. The irradiation of α-position proton signal for the free pyridine decreased the integral values of the proton signal for coordinating pyridyl group by spin-saturation transfer process **(Fig. S9)**. The rate constant k_{obs} was determined according to the equation (1), where T_{1py} = spin relaxation time of the free pyridine, M_{py} = the net magnetization of the free pyridine, and M_{0py} = the net magnetization of the free pyridine at thermal equilibrium.

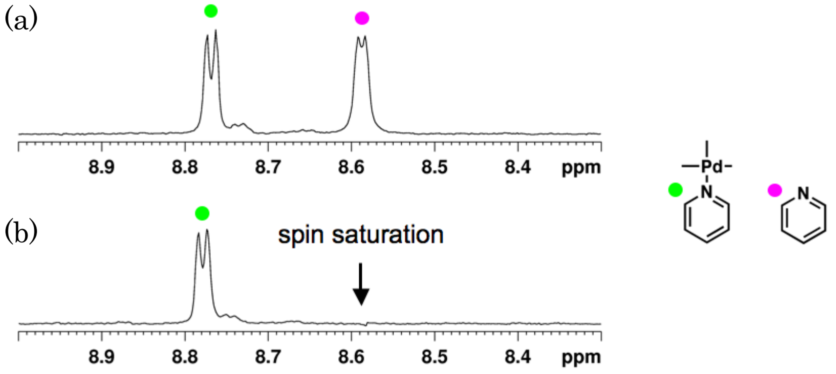


Fig. S9. ^{1}H NMR spectra for spin-saturation transfer experiment (500 MHz, CD_3CN, 300 K). (a) Reference NMR spectrum for the region of α-protons of pyridine. (b) Spin saturation transfer spectrum with irradiation at an arrow position.

$$k_{obs} = \frac{1}{T_{1py}}\left(\frac{M_{0py}}{M_{py}} - 1\right) \qquad (1)$$

References

(1) Liu, M.; Mao, X.; Ye, C.; Huang, H.; Nicholson, J. K.; Lindon, J. C. *J. Magn. Reson.* **1998**, *132*, 125-129.

(2) Jarek, R. L.; Flesher, R. J.; Shin, S. K. *J. Chem. Educ.*, **1997**, *74*, 978-982.