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Nanoscale Borromeates

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In addition to a parent zinc(II) Borromean ring (BR) complex, the preparation and characterization of two hexasubstituted BR complexes with either 4-acetoxymethylphenyl or 4-methylthiophenyl substituents associated in turn with all six pyridyl rings has been achieved convergently in good yields by appealing to the dynamic features of the reactions between primary amino groups in a preformed acyclic ligand and 2,6-diformylpyridine. Two molecules of the acyclic ligands react with two molecules of 2,6-diformylpyridine to form a cyclic [2 + 2] tetraimine in the presence of Zn(II) ions as templates in 2-propanol at 70 °C. The successful preparation of the two derivatives by convergent template-directed syntheses opens up opportunities to self-assemble, under equilibrium control, numerous nanoscale metallo-organic particles with potentially useful properties.

Recently, we reported[1] the near-quantitative self-assembly of a nanoscale Borromean ring (BR) compound from 18 components by the template-directed formation of 30 dative bonds and 12 imine bonds. The highly efficient synthesis involves the coordination of three interlocked macrocycles, each tetranucleating overall, to a total of six zinc(II) ions (Figure 1). The successful construction of this topologically unique molecular structure[2] is rooted in the cooperative interactions that exist between coordinating metal−ligand bonds, consequent upon imine bond formation, that are aided and abetted by 12 $\pi-\pi$ stacking interactions between π-donating and π-accepting aromatic rings buried in the nether regions of the shell of the molecule, which is 2.5 nm in diameter and has an inner cavity of 250 Å^3 in volume. The fundamental principles that govern the molecular recognition associated with the self-assembly are to be found deep within the realms of dynamic covalent chemistry[3,4] with coordination[5] and supramolecular[6] chemistry helping to provide the necessary stereoelectronic control under equilibrating conditions where proof-reading and error-checking are operative.

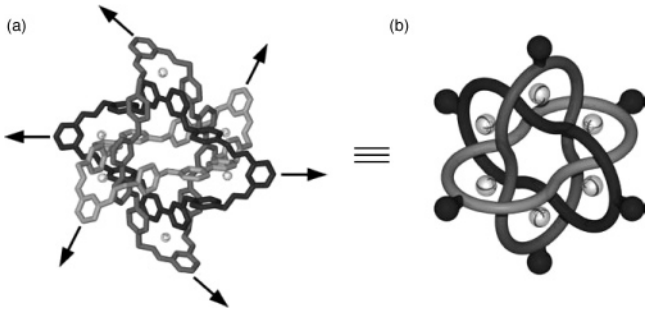

FIGURE 1. Two representations of the Borromean rings as observed (a) in the solid-state X-ray structure of the parent zinc(II) Borromean ring complex where the arrows indicate the 4-positions on the pyridine rings and (b) graphically, highlighting, with handles, the six positions for exohedral synthetic modifications.

Since completing the template-directed synthesis[7] of our first metallo-BR complex[1] or Borromeate,[8,9] we have probed the reversible nature associated with the 30 dative and the 12 imine bonds by conducting ligand-exchange experiments[8] in acidic methanolic solutions of

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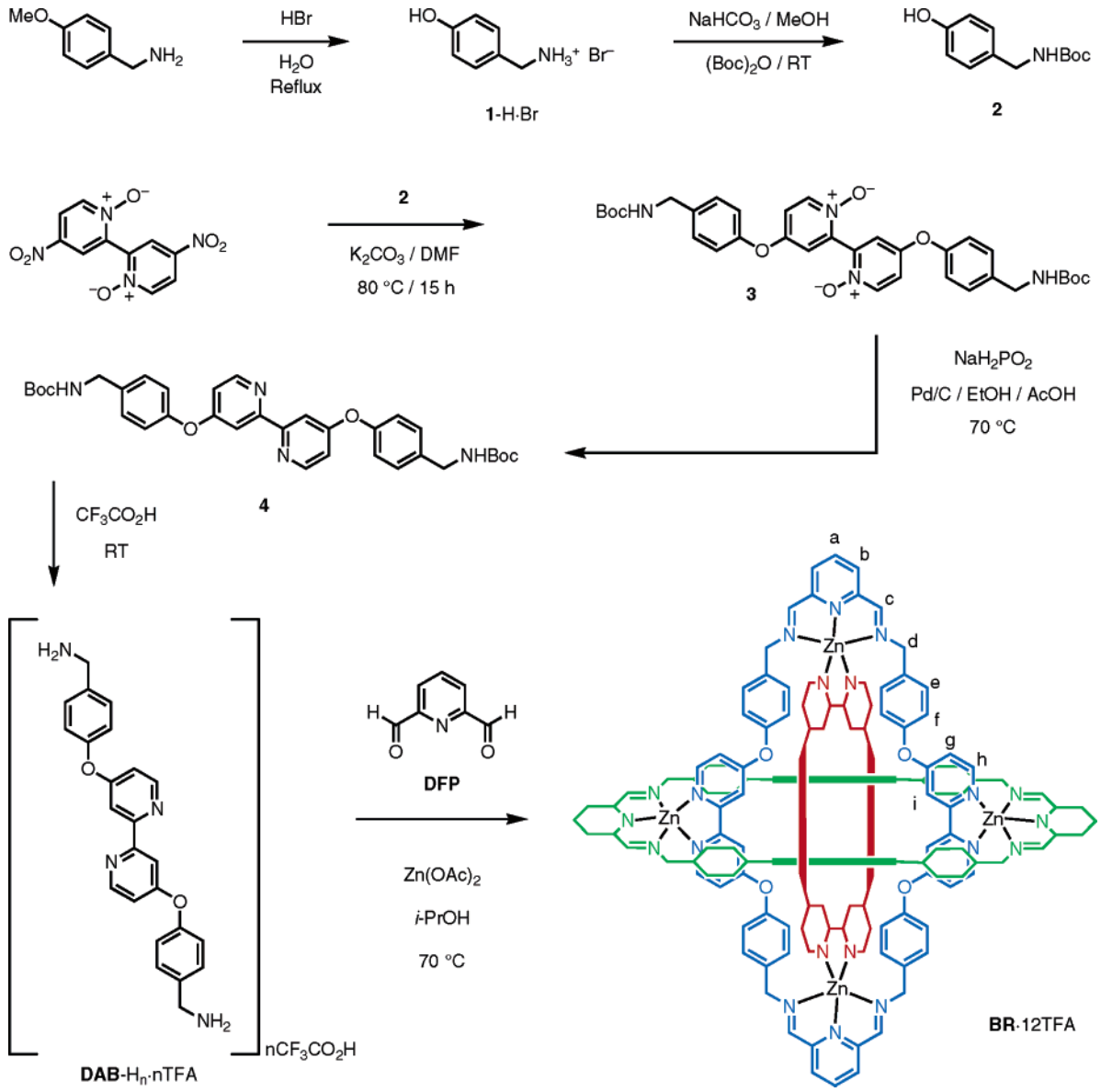
SCHEME 1. Synthesis of the Dibenzylammonium Bipyridine Trifluoroacetate Salt (DAB) and BR·12TFA



the hexachloro-BR and hexabromo-BR derivatives where the halogen atom labels are sited at the 4-positions of the six pyridine rings that eventually become the six *endo* tridentate bis-Schiff base ligands in the Borromeate structure. These positions also afford by far the easiest way to introduce functionality onto the surfaces of these metallo-organic nanoparticles by carrying out their template-directed synthesis[7] with 4-substituted 2,6-diformylpyridines in place of the 2,6-diformylpyridine (**DFP**) in a reaction between **DFP** and a diamine (**DAB**) containing the incipient six *exo* bidentate ligands. Here, we report the synthesis of the parent zinc(II) metallo-BR complex as well as two derivatives that illustrate the synthetic potential of this Borromeate structure to serve as a hexavalent metallo-organic core.

Results and Discussion

The diamine **DAB** containing a bipyridyl ligand was obtained (Scheme 1) as its $n CF_3CO_2^-$ salt, **DAB**-H_n·

(3) For a few glimpses at the rapidly growing literature on dynamic covalent chemistry, see: (a) Rowan, S. J.; Brady, P. A.; Sanders, J. K. M. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2143-2145. (b) Lehn, J.-M.; Eliseev, A. V. *Science* **2001**, *291*, 2331−2332. (c) Ramström, O.; Lehn, J.-M. *Nat. Rev. Drug Discov.* **2002**, *1*, 26−36. (d) Otto, S.; Furlan, R. L. E.; Sanders, J. K. M. *Science* **2002**, *297*, 590−593. (e) Rowan, S. J.; Cantrill, S. J.; Cousins, G. R. L.; Sanders, J. K. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2002**, *41*, 898−952. (f) Otto, S. *Curr. Opin. Drug Discov. Devel.* **2003**, *6*, 509−520. (g) Brisig, B.; Sanders, J. K. M.; Otto, S. *Angew. Chem., Int. Ed.* **2003**, *42*, 1270−1273. (h) Fuchs, B.; Nelson, A.; Star, A.; Stoddart, J. F.; Vidal, S. B. *Angew. Chem., Int. Ed.* **2003**, *42*, 4220−4224. (i) Lam, R. T. S.; Belenguer, A.; Roberts, S. L.; Naumann, C.; Jarrosson, T.; Otto, S.; Sanders, J. K. M. *Science* **2005**, *308*, 667−669.

(4) Reversible imine bond formation and exchange has been employed successfully in the synthesis of rotaxanes. For stoppering approaches to rotaxanes incorporating imine-containing dumbbells, see: (a) Cantrill, S. J.; Rowan, S. J.; Stoddart, J. F. *Org. Lett.* **1999**, *1*, 1363−1366. (b) Rowan, S. J.; Stoddart, J. F. *Org. Lett.* **1999**, *1*, 1913−1916. (c) For clipping approaches to rotaxanes incorporating imine-containing macrocycles, see: (c) Glink, P. T.; Oliva, A. I.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *Angew. Chem., Int. Ed.* **2001**, *40*, 1870−1875. (d) Horn, M.; Ihringer, J.; Glink, P. T.; Stoddart, J. F. *Chem. Eur. J.* **2003**, *9*, 4046−4054. (e) Hogg, L.; Leigh, D. A.; Lusby, P. J.; Morelli, A.; Parsons, S.; Wong, J. K. Y. *Angew. Chem., Int. Ed.* **2004**, *43*, 1218−1221. (f) Aricó, F.; Chang, T.; Cantrill, S. J.; Khan, S. I.; Stoddart, J. F. *Chem. Eur. J.* **2005**, *11*, 4655−4666.

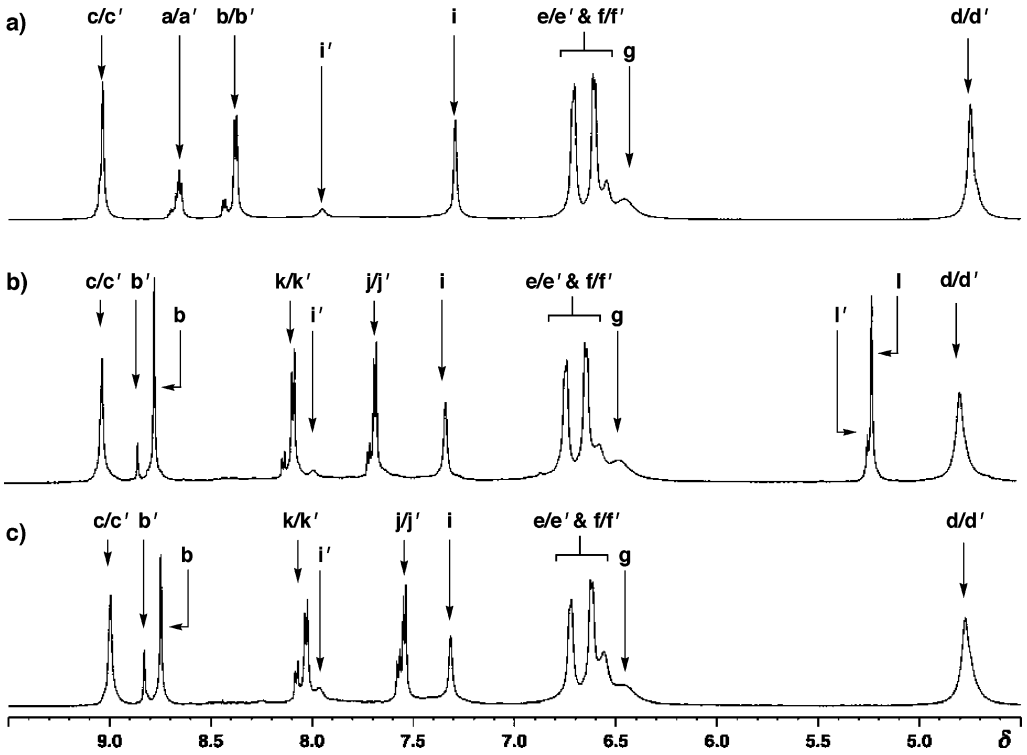


FIGURE 2. ^{1}H NMR (600 MHz, CD_3SOCD_3, 25 °C) spectra of the (a) **BR**·12TFA and **Zn@BR**·14TFA, (b) **BR(C$_6$H$_4$CH$_2$OAc)**·12TFA and **Zn@BR(C$_6$H$_4$CH$_2$OAc)**·14TFA, and (c) **BR(C$_6$H$_4$SMe)**·12TFA and **Zn@BR(C$_6$H$_4$SMe)**·14TFA complexes. The letters **a**−**l** have been designated on structural formulas in Schemes 1 and 3.

*n*TFA, in five steps starting from 4-methoxybenzylamine. Its demethylation in refluxing 48% HBr afforded (92%) the hydrobromide[10] **1**−H·Br of 4-hydroxybenzylamine. When this salt was treated with 1.1 equiv of (*t*-Boc)$_2$O in a methanolic suspension of $NaHCO_3$, the *tert*-butyloxycarbonyl-protected amine **2** was isolated in 93% yield. In the meantime, the bipyridyl *N*,*N*′-dioxide **3** had been prepared by the treatment of 4,4′-dinitro-2,2′-bipyridyl *N*,*N*′-dioxide with the potassium salt of **2** in anhydrous DMF at 80 °C. Compound **4** was obtained in 92% yield as a result of the catalytic transfer hydrogenolysis[11] of **3** using 10% Pd/C with NaH_2PO_2 as the source of H_2 in a mixture of EtOH/AcOH under mild conditions. In the final step, **DAB**-H$_n$·*n*TFA was isolated in almost quantitative yield (95%) following *t*-Boc deprotection using CF_3CO_2H.

The template-directed self-assembly of **BR**·12TFA was achieved almost quantitatively in *i*-PrOH by heating equimolar amounts (0.10 mM) of **DFP**, freshly deprotected **DAB**-H$_n$·nTFA, and $Zn(OAc)_2$ at 70 °C for 24 h. From the point of view of controlling stoichiometry, it proved advantageous to avoid the use of isolated **DAB**-H$_n$·*n*TFA as it exists undoubtedly as a mixture of tris- and tetrakis-TFA salts. By following this protocol, **BR**·12TFA was isolated as an off-white solid in 95% yield by filtration of the reaction mixture. Close inspection of the ^{1}H NMR spectrum revealed that the product is a mixture of **BR**·12TFA and a complex, **Zn@BR**·14TFA, in which an additional Zn(II) ion has been trapped within the molecule, in a ratio of 86:14. The admixture is evidenced by the additional signals observed in the ^{1}H NMR spectrum (Figure 2a) recorded[12] in CD_3SOCD_3. The large chemical shift difference for the proton (H-i/i′), which is pointing into the cavity of the **BR**$^{12+}$ dodecacation, supports the hypothesis that a seventh Zn(II) ion is

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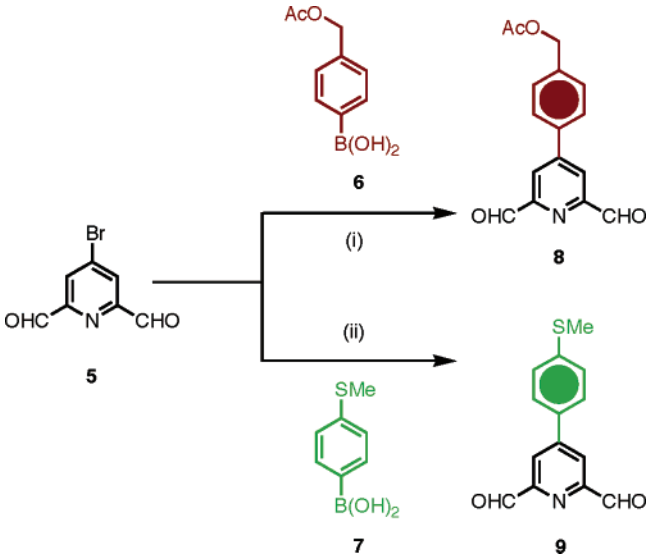
(12) A much better resolved ^{1}H NMR spectrum (see the Supporting Information) can be obtained by recording it in CD_3OD solution. The reason for using CD_3SOCD_3 as the solvent relates to the need to make comparisons with two other hexasubstituted derivatives which are not both easily soluble in CD_3OD.

SCHEME 2. Synthesis of the 4-Substituted 2,6-Diformylpyridines[a]



[a] Key: (i) $Pd(PPh_3)_4/NaHCO_3/PhMe/H_2O$, 90 °C, 15 h; (ii) $Pd(PPh_3)_4/NaHCO_3/H_2O/THF$, 85 °C, 15 h.

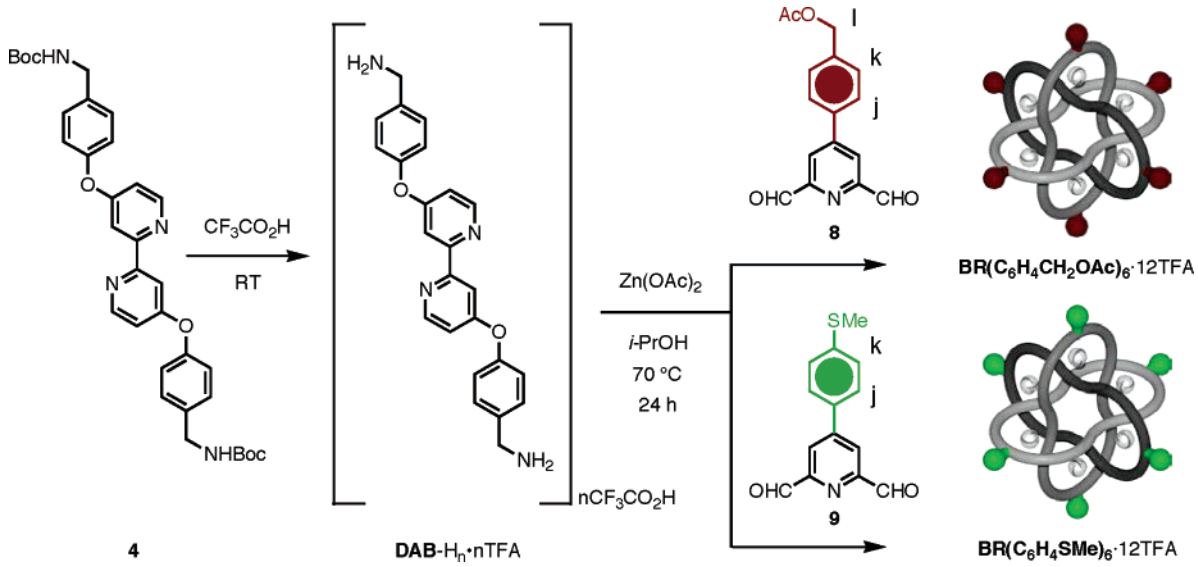
trapped therein. Other protons (H-a/a′, H-b/b′, H-c/c′, H-e/e′, H-f/f′) on the periphery of the molecule are only ever so slightly shifted, depending on whether the cavity is occupied by a Zn(II) ion or not. The appearance[13] of additional peaks corresponding to **Zn@BR**·14TFA in the ESI mass spectrum were not observed. Only peaks at *m/z* 1465, 1070, and 834 corresponding to $[M - 3TFA]^{3+}$, $[M - 4TFA]^{4+}$ and $[M - 5TFA]^{5+}$, respectively, where M represents the fully assembled **BR**·12TFA complex, were present in the spectrum.

In principle, it is conceivable to try to produce derivatives of **BR**·12TFA by carrying out either pre-assembly or post-assembly covalent modifications. Although it does depend on what type (kinetically or thermodynamically controlled) of chemical reactions are employed, post-assembly modifications will, more often than not, be done under kinetic control, leading to a complex mixture of up to 10 possible different products. Thus, it is much easier to prepare hexasubstituted homo-BR complexes by following the protocol of pre-assembly covalent modifications of the components, provided that the substituents which are being introduced are stable to the conditions of the self-assembly process. In this manner, all of the kinetic penalties that accompany covalent bond-forming reactions are paid before the assembly step that operates under thermodynamic control. It is an approach that makes it relatively easy to introduce (Figure 1) substituents onto the 4-positions of the 2,6-diformylpyridine component prior to the thermodynamically controlled self-assembly step that will then lead to the formation of the hexasubstituted homo-BR derivatives in high yields.

The relative ease by which large quantities of 4-bromo-2,6-diformylpyridine[14] (**5**) can be synthesized singles it out as an ideal candidate for introducing substituents onto the periphery of the BR scaffold by employing the efficient Suzuki-type palladium-catalyzed cross-coupling reactions of aryl boronic acids. The synthesis of two 4-aryl-2,6-diformylpyridines shown in Scheme 2 follows this protocol. 4-Acetoxymethylphenylboronic acid[15] (**6**) and 4-methylthiophenylboronic acid[16] (**7**) were coupled to **5** to afford the aryl-substituted dialdehydes **8** and **9** in good yields, respectively. In the case of **8**, reactions that were carried out in aqueous THF had a detrimental effect on the yield, suggesting that significant amounts of the ester group was hydrolyzed under increasingly aqueous conditions. The hydrolysis of the ester group was minimized by carrying out this coupling reaction in $PhMe/H_2O$ (30:4) saturated with $NaHCO_3$, conditions which reduce the total water content in the organic phase, affording **8** in excellent yields.

The formation of the corresponding BR complexes incorporating these aryl substituents is outlined in Scheme 3. They are assembled from equimolar mixtures (0.07 mM) of either **8** or **9** with $Zn(OAc)_2$ and the freshly deprotected diaminobipyridyl ligand **DAB**-H_n·*n*TFA in alcoholic solutions which were heated at 70 °C for 24 h. In both cases, the aryl-BR complexes **BR**$(C_6H_4CH_2OAc)_6$·12TFA and **BR**$(C_6H_4SMe)_6$·12TFA precipitated out from

SCHEME 3. Self-Assembly of the Hexasubstituted Borromeates



the reaction mixtures and were isolated by filtering the solutions to afford air-stable solids in 97% and 89% yields, respectively. The ^{1}H NMR spectra of these products in CD_3SOCD_3 revealed (Figure 2b,c) that they have been isolated as mixtures of the empty BR compounds and filled—each with a Zn(II) ion—BR complexes. A set of duplicate signals (primed letters) of lower intensities, corresponding to the Zn@BR complexes are evident in the spectrum. Apart from these additional signals, singlets at δ 9.02 and 9.00 ppm for the imine protons in **BR(C$_6$H$_4$CH$_2$OAc)$_6$**·12TFA and **BR(C$_6$H$_4$SMe)$_6$**·12TFA are consistent with the successful formation of the chelated bis-Schiff base tridentate ligands. In addition to the presence of these diagnostic signals for the highly symmetrical BR complexes, the two pairs of protons for the aryl substituents on the **DAB** units are significantly shifted upfield, a situation that is consistent with them being π-stacked around matching bipyridyl ligands in the orthogonally disposed macrocycle. All this molecular recognition is evident in the solid-state structure (Figure 1) of **BR**·12TFA. ESI mass spectrometric analysis of these two products revealed three major peaks at *m/z* values at 1760, 1292, and 1011 for **BR(C$_6$H$_4$CH$_2$OAc)$_6$**·12TFA and also at 1709, 1253, and 980 for **BR(C$_6$H$_4$SMe)$_6$**·12TFA, arising from the $[M - 3TFA]^{3+}$, $[M - 4TFA]^{4+}$, and $[M - 5TFA]^{5+}$ ions, respectively, where M represents the mass of the fully assembled BR complexes.

Thus, we have prepared and characterized, in addition to the parent Borromeate **BR**·12TFA, two new hexasubstituted BR complexes as a result of conducting template-directed syntheses, starting from readily available components. Suzuki cross-coupling reactions make it possible to append substituents to the 4-position on **DFP**. The synthetic approach, which has been developed successfully and reported here in detail, will surely aid future synthetic modifications of these nanoscale metallo-organic particles.

Experimental Section

4-Hydroxybenzylammonium Bromide (1—H·Br). The following procedure is a modified one based on that reported[10] in the patent literature. When 4-methoxybenzylamine (11.6 g, 84.6 mmol) was added with stirring to 48% HBr (30 mL), a precipitate was formed. *Since an extremely exothermic reaction ensues, the addition was done very slowly*. The mixture was then stirred under reflux for 6 h before being cooled to room temperature and concentrated to dryness, giving a light pink solid. MeCN (20 mL) was added to this residue, and the product **1**—H·Br was collected by filtration and dried under vacuum. Yield: 16.2 g, 92%. The product was identified by ^{1}H NMR spectroscopy and employed in the next step without further purification. ^{1}H NMR (500 MHz, D_2O, 25 °C): δ 3.95 (s, 2H), 6.79 (d, J = 8.6 Hz, 2H), 7.19 (d, J = 8.6 Hz, 2H).

***tert*-Butyl (4-Hydroxybenzyl)carbamate (2).** Di-*tert*-butyl dicarbonate (18.5 g, 84.8 mmol) was added with stirring under an atmosphere of argon to a solution of **1**—H·Br (16.0 g, 78.4 mmol) and $NaHCO_3$ (26.3 g, 313 mmol) in MeOH (200 mL) at room temperature. After the reaction mixture was stirred for 24 h, it was filtered to remove excess of $NaHCO_3$. The solvents were removed under reduced pressure, and the oily residue was purified by column chromatography [SiO_2: EtOAc/hexanes (1:4)] to afford **2** as a yellow oil. Yield: 16.2 g, 93%. ^{1}H NMR (500 MHz, CD_2Cl_2, 25 °C): δ 1.46 (s, 9H), 4.19 (d, J = 5.5 Hz, 2H), 5.09 (bs, 1H), 6.77 (d, J = 8.5 Hz, 2H), 6.96 (bs, 1H), 7.09 (d, J = 8.1 Hz, 2H). ^{13}C NMR (125 MHz, CD_2Cl_2, 25 °C): δ 28.5, 44.4, 115.8, 129.1, 130.8, 156.0. HRMS (MALDI): *m/z* 246.1100 $[M + Na]^+$.

4,4′-(*tert*-Butyl (4-hydroxybenzyloxy)carbamate)-2,2′-bipyridyl *N,N*′-Dioxide (3). Solid K_2CO_3 (8.0 g, 58 mmol) was added to a stirred solution of **2** (9.00 g, 40.3 mmol) and 4,4′-dinitro-2,2′-bipyridyl *N,N*′-dioxide (4.50 g, 16.2 mmol) in anhydrous DMF (30 mL) under an argon atmosphere, and the reaction mixture was heated at 80 °C for 15 h. Thereafter, the solution was cooled to room temperature, and the solvents were removed under reduced pressure, leaving a yellow-brown solid residue. H_2O (300 mL) was added to this residue, and the resulting mixture was sonicated until a suspended solid was produced. The suspension was removed by filtration, washed with H_2O, and dried to afford a light-yellow solid (10.1 g). The solid was then dissolved in CH_2Cl_2 (200 mL) and diluted with EtOAc (300 mL). This solution was brought to a boil and concentrated to 300 mL. The title compound **3** precipitates from the mixture upon cooling and is collected by filtration and dried. Yield: 8.03 g, 78%. Mp: 217—218 °C (EtOAc). ^{1}H NMR (500 MHz, CD_2Cl_2, 25 °C): δ 1.44 (s, 18H), 4.08 (d, J = 5.8 Hz, 4H), 5.12 (bs, 2H), 6.92 (dd, J = 3.5, 7.3 Hz, 2H), 7.08 (d, J = 8.5 Hz, 4H), 7.15 (d, J = 3.5 Hz, 2H), 7.34 (d, J = 8.5 Hz, 4H), 8.12 (d, J = 7.3 Hz, 2H). ^{13}C NMR (125 MHz, CD_2Cl_2, 25 °C): δ 28.5, 44.1, 115.8, 116.6, 120.8, 129.6, 137.5, 141.1, 143.0, 153.7, 155.2. HRMS (MALDI): *m/z* 631.2762 $[M + H]^+$.

4,4′-Bis(4-*tert*-butyl-*N*-phenoxycarbamate)-2,2′-bipyridine (4). The following procedure is a modified one based on that reported[11] for the deoxygenation of 2,2′-bipyridyl *N,N*′-dioxide. An excess of NaH_2PO_2 (5.00 g, 55.0 mmol) was added in one portion to a three-necked flask equipped with a condenser containing a stirred suspension of **3** (5.00 g, 7.93 mmol) and 10% Pd/C (1.00 g) in 75/15 EtOH/AcOH (90 mL). The reaction flask was sealed with a balloon to prevent the loss of the H_2 gas which evolves from the decomposition of NaH_2PO_2, and the mixture was heated at 70 °C for 15 h. The reaction mixture was cooled to room temperature and filtered through Celite. The filter cake was washed with CH_2Cl_2 (3 × 100 mL). The filtrates were combined, and the volume was concentrated to 50 mL under reduced pressure, giving a light yellow solution. The AcOH was neutralized by adding solid $NaHCO_3$ (6 g) in H_2O (50 mL). The solution was concentrated to dryness, producing a beige product which was suspended in H_2O, collected by filtration, washed with H_2O, and dried. Yield: 4.32 g, 92%. The crude product was recrystallized from EtOAc/hexanes, affording **4** as fine white needles. Yield: 3.72 g, 78%. Mp: 158—160 °C. ^{1}H NMR (500 MHz, CD_2Cl_2, 25 °C) δ 1.45 (s, 18H), 4.33 (d, J = 7.1 Hz, 4H), 5.04 (bs, 2H), 6.86 (dd, J = 3.5, 7.3 Hz, 2H), 7.11 (d, J = 8.5 Hz, 4H), 7.37 (d, J = 8.5 Hz, 4H), 7.92 (d, J = 3.5 Hz, 2H), 8.44 (d, J = 7.3 Hz, 2H). ^{13}C NMR (125 MHz, CD_2Cl_2, 25 °C) δ 28.5, 44.2, 109.3, 112.9, 121.2, 129.5, 137.0, 151.0, 153.7, 158.1, 166.1. HRMS (MALDI): *m/z* 621.2684 $[M + Na]^+$.

DAB-H$_n$·*n*TFA. The Boc protecting groups in **4** were removed by the addition of CF_3CO_2H (4 mL) to solid **4** (1.00 g, 1.67 mmol) with stirring at room temperature for 10 min. The reaction mixture was concentrated to dryness, leaving a sticky residue. The excess of CF_3CO_2H was removed by three

(13) Samples which contain upwards of 50% of the **Zn@BR**·14TFA complex do reveal peaks at *m/z* 1563 and 1143 corresponding to $[M - 3TFA]^{3+}$ and $[M - 4TFA]^{4+}$ ions, respectively, where M represents the mass of the **Zn@BR**·14TFA complex. See ref 1.

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repeated additions and removal of MeOH (20 mL) by rotary evaporation under reduced pressure at 50 °C, leaving a pink sticky residue. This residue was treated with CH_2Cl_2, and the solvent was removed by rotary evaporation under reduced pressure at 40 °C until a light pink amorphous solid remained that is moisture sensitive. Yield of crude **DAB**-H_n·*n*TFA: 1.32 g, 95%. ^{1}H NMR (500 MHz, CD_3OD, 25 °C): δ 4.20 (s, 4H), 7.18 (dd, J = 3.5, 7.3 Hz, 2H), 7.33 (d, J = 8.5 Hz, 4H), 7.64 (d, J = 8.5 Hz, 4H), 8.06 (d, J = 3.5 Hz, 2H), 8.66 (d, J = 7.3 Hz, 2H). ^{13}C NMR (125 MHz, CD_3OD, 25 °C) δ 43.6, 112.8, 114.8, 117.9 (q, J = 291 Hz, TFA), 122.6, 132.8, 133.0, 149.8, 152.2, 155.2, 162.3 (q, J = 35.5 Hz, TFA) 170.0. HRMS (ESI): *m/z* 399.1836 (100) $[M - 4CF_3CO_2H + H]^+$, 819.3428 (62) $[2M - 8CF_3CO_2H + Na]^+$.

4-(4-Acetoxymethylphenyl)-2,6-diformylpyridine (8). 4-Bromo-2,6-diformylpyridine (**5**) (500 mg, 2.34 mmol), 4-acetoxymethylphenyl boronic acid (**6**) (453 mg, 2.34 mmol), and tetrakistriphenylphosphine palladium(0) (265 mg, 0.23 mmol) were added to a degassed PhMe (30 mL) solution containing $NaHCO_3$ (2.0 g) and H_2O (4 mL). The reaction mixture was then heated under an inert atmosphere of argon at 90 °C for 15 h. The solvents were removed by rotary evaporation, and the resulting residue was purified by column chromatography [SiO_2: CH_2Cl_2] to yield the title compound **8** as a white solid (610 mg). Recrystallized from CH_2Cl_2/hexanes (524 mg). Yield: 79%. Mp: 139−141 °C. ^{1}H NMR (500 MHz, CD_2Cl_2, 25 °C): δ 2.13 (s, 3H), 5.17 (s, 2H), 7.54 (d, J = 8.4 Hz, 2H), 7.79 (d, J = 8.4 Hz, 2H), 8.39 (s, 2H), 10.20 (s, 2H). ^{13}C NMR (150 MHz, CD_2Cl_2, 25 °C): δ 21.1, 65.7, 123.0, 127.7, 129.2, 136.0, 139.0, 150.9, 154.1, 170.9, 192.8. HRMS (EI): *m/z* 283.0850.

4-(4-Methylthiophenyl)-2,6-diformylpyridine (9). 4-Bromo-2,6-diformylpyridine (**5**) (500 mg, 2.34 mmol), 4-methylthiophenyl boronic acid (**7**) (453 mg, 2.34 mmol), and tetrakistriphenylphosphinepalladium(0) (265 mg, 0.23 mmol) were added to a degassed 1:1 THF/H_2O (20 mL) solution containing $NaHCO_3$ (2.0 g). The reaction mixture was then heated under an inert atmosphere of argon at 85 °C for 15 h. The reaction mixture was transferred to a separatory funnel containing H_2O (50 mL), and the aqueous solution was extracted with CH_2Cl_2 (3 × 100 mL). The combined organic layers were dried ($MgSO_4$) and filtered, and the solvents were removed by rotary evaporation. The resulting residue was purified by column chromatography [SiO_2: CH_2Cl_2] to yield the title compound **9** as a light yellow solid. Recrystallized from EtOAc/hexanes (502 mg). Yield: 83%. Mp: 168−170 °C. ^{1}H NMR (500 MHz, CD_2Cl_2, 25 °C): δ 2.13 (s, 3H), 5.17 (s, 2H), 7.54 (d, J = 8.4 Hz, 2H), 7.79 (d, J = 8.4 Hz, 2H), 8.39 (s, 2H), 10.20 (s, 2H). ^{13}C NMR (150 MHz, CD_2Cl_2, 25 °C): δ 21.1, 65.7, 123.0, 127.7, 129.2, 136.0, 139.0, 150.9, 154.1, 170.9, 192.8. HRMS (EI): *m/z* 257.0512.

BR·12TFA and Zn@BR·14TFA. Compound **4** (600 mg, 1.00 mmol) was dissolved in TFA (5 mL) and stirred at room temperature for 10 min. Excess TFA was removed by rotary evaporation under reduced pressure followed by subsequent additions and removals of MeOH (3 × 5 mL), leaving a pink tar. $Zn(OAc)_2$ (183.0 mg, 1.00 mmol) was added to a stirred *i*-PrOH (10 mL) solution containing the freshly deprotected **DAB**-H_n·*n*TFA, followed by **DFP** (135 mg, 1.00 mmol), and the reaction mixture was heated at 70 °C for 24 h, producing an off-white precipitate which was removed by filtration, washed with *i*-PrOH and Et_2O, and dried to afford the title compound as a mixture of **BR**·12TFA and **Zn@BR**·14TFA (86:14) as an off-white powder. Yield: 754 mg, 95%. ^{1}H NMR data for **BR**·12TFA (600 MHz, CD_3OD, 25 °C): δ 4.84 (s, 24H), 6.50 (bs, 12H), 6.69 (d, J = 8.5 Hz, 24H), 6.73 (d, J = 8.5 Hz, 24H), 7.97 (d, J = 2.4 Hz, 12H), 8.31 (d, J = 7.8 Hz, 12H), 8.61 (t, J = 7.8 Hz, 6H), 8.89 (s, 12H). ^{1}H NMR data for **Zn@BR**·14TFA (600 MHz, CD_3OD, 25 °C): δ 4.74 (d, J = 14 Hz, 12H), 4.80 (d, J = 14 Hz, 12H), 6.57 (d, J = 8.4 Hz, 24H), 6.61 (d, J = 8.4 Hz, 24H), 7.30 (d, J = 5.4 Hz, 12H), 8.20 (d, J = 2.4 Hz, 12H), 8.34 (d, J = 7.8 Hz, 12H), 8.63 (t, J = 7.8 Hz, 6H), 8.92 (s, 12H). ^{1}H NMR data for **BR**·12TFA and **Zn@BR**·14TFA (600 MHz, CD_3SOCD_3, 25 °C): δ 4.75 (bs, 24H), 6.46 (bs, 12H), 6.55 (bs, 48H), 6.61 (bd, J = 6.6 Hz, 24H), 6.70 (bd, 24H), 7.29 (bs, 12H), 7.95 (bs, 12H), 8.38 (d, J = 7.2 Hz, 12H), 8.43 (d, J = 7.8 Hz, 12H), 8.66 (t, J = 7.2 Hz, 6H), 8.70 (t, J = 7.8 Hz, 6H), 9.03 (s, 12H), 9.05, (s, 12H). ^{13}C NMR of **BR**·12TFA (150 MHz, CD_3OD, 25 °C): δ 63.1, 112.6, 113.9, 117.9 (q, J = 296 Hz, TFA), 122.3, 130.8, 131.2, 135.1, 145.5, 148.2, 151.7, 153.3, 162.0, 162.5 (q, J = 34.6 Hz, TFA) 169.8. ^{13}C NMR data for **BR**·12TFA and **Zn@BR**·14TFA (125 MHz, CD_3SOCD_3, 25 °C): δ 60.8, 109.7, 111.4, 114.3, 116.9 (q, J = 298 Hz, TFA), 120.6, 129.6, 130.8, 133.6, 144.2, 146.2, 146.6, 148.9, 149.9, 151.1, 153.3,158.1 (q, J = 31.6 Hz, TFA),160.7, 163.8, 167.3. HRMS (ESI): *m/z* 1465.1902 (10) $[M - 3CF_3CO_2]^{3+}$, 1070.1398 (100) $[M - 4CF_3CO_2]^{4+}$, 833.7088 (50) $[M - 5CF_3CO_2]^{5+}$.

BR($C_6H_4CH_2OAc$)$_6$·12TFA and Zn@BR($C_6H_4CH_2OAc$)$_6$·14TFA. Compound **4** (220 mg, 0.367 mmol) was dissolved in TFA (2 mL) and stirred at room temperature for 10 min. Excess TFA was removed by rotary evaporation under reduced pressure followed by subsequent additions and removals of MeOH (3 × 5 mL), leaving a pink tar. $Zn(OAc)_2$ (67.0 mg, 0.367 mmol) was added to a stirred *i*-PrOH solution (5 mL) containing the freshly deprotected **DAB**-H_n·*n*TFA, followed by **8** (104 mg, 0.367 mmol) dissolved in CH_2Cl_2 (1 mL). The reaction mixture was first heated to remove CH_2Cl_2 solvents and then at 70 °C for 24 h, producing an off-white colored precipitate which was removed by filtration, washed with *i*-PrOH and Et_2O, and dried to afford the title compound as a mixture of **BR($C_6H_4CH_2OAc$)$_6$**·12TFA and **Zn@BR($C_6H_4CH_2OAc$)$_6$**·14TFA (86:14) as a light orange powder. Yield: 336 mg, 97%. The product can be crystallized from a methanolic solution into which Et_2O was allowed to diffuse slowly. ^{1}H NMR data for **BR($C_6H_4CH_2OAc$)$_6$**·12TFA (600 MHz, CD_3OD, 25 °C): δ 2.12 (s, 18H), 4.86 (s, 24H), 5.23 (s, 12H), 6.52 (bs, 12 H), 6.71 (d, J = 7.8 Hz, 24H), 6.76 (d, J = 7.8 Hz, 24H), 7.65 (d, J = 8.4 Hz, 12H), 8.00 (d, J = 4.2 Hz, 12H), 8.03 (d, J = 8.4 Hz, 12H), 8.63 (s, 12H), 8.93 (s, 12H). ^{1}H NMR data for **Zn@BR($C_6H_4CH_2OAc$)$_6$**·14TFA (600 MHz, CD_3OD, 25 °C): δ 2.14 (s, 18H), 4.76 (d, J = 14 Hz, 12H), 4.81 (d, J = 14 Hz, 12H), 5.25 (s, 12H), 6.58 (d, J = 8.6 Hz, 24H), 6.63 (d, J = 8.6 Hz, 24H), 7.31 (bs, 12H), 7.67 (d, J = 8.6 Hz, 12H), 8.06 (d, J = 8.6 Hz, 12H), 8.16 (bs, 12H), 8.23 (d, J = 2.1 Hz, 12H), 8.65 (s, 12H), 8.94 (s, 12H). ^{1}H NMR data for **BR($C_6H_4CH_2OAc$)$_6$**·12TFA and **Zn@BR($C_6H_4CH_2OAc$)$_6$**·14TFA (600 MHz, CD_3SOCD_3, 25 °C): δ 2.12 (s, 12H), 2.14 (s, 12H), 4.78 (bs, 24H), 5.21 (s, 12H), 5.24 (s, 12H), 6.46 (bs, 12H), 6.56 (bs, 48H), 6.62 (bd, J = 6.6 Hz, 24H), 6.73 (bd, J = 6.6 Hz, 24H), 7.32 (bs, 12H), 7.67 (d, J = 8.4 Hz, 12H), 7.70 (d, J = 8.4 Hz, 12H), 8.07 (d, J = 8.4 Hz, 12H), 8.12 (d, J = 8.4 Hz, 12H), 8.76 (s, 12H), 8.84 (s, 12H), 9.02, (s, 12H). ^{13}C NMR data for **BR($C_6H_4CH_2OAc$)$_6$**·12TFA and **Zn@BR($C_6H_4CH_2OAc$)$_6$**·14TFA (150 MHz, CD_3SOCD_3, 25 °C): δ 20.7, 61.0, 64.8, 109.8, 111.4, 115.5, 117.0 (q, J = 298 Hz, TFA), 120.7, 126.6, 127.6, 128.9, 129.0, 129.6, 133.6, 134.5, 139.6, 146.9, 147.3, 149.0, 150.0, 151.2, 153.4, 153.9, 158.2 (q, J = 32.6 Hz, TFA), 160.6, 163.8, 167.4 170.3. HR-ESI-MS: *m/z* 1760.9303 (50) $[M - 3CF_3CO_2]^{3+}$, 1292.4819 (100) $[M - 4CF_3CO_2]^{4+}$, 1011.3981 (20) $[M - 5CF_3CO_2]^{5+}$.

BR(C_6H_4SMe)$_6$·12TFA and Zn@BR(C_6H_4SMe)$_6$·14TFA. Compound **4** (209 mg, 0.350 mmol) was dissolved in TFA (2 mL) and stirred at room temperature for 10 min. Excess TFA was removed by rotary evaporation under reduced pressure, followed by subsequent additions and removals of MeOH (3 × 5 mL), leaving a pink tar. $Zn(OAc)_2$ (64.0 mg, 0.350 mmol) was added to a stirred *i*-PrOH solution (5 mL) containing the freshly deprotected **DAB**-H_n·*n*TFA, followed by **9** (90 mg, 0.350 mmol) dissolved in CH_2Cl_2 (1 mL). The reaction mixture was first heated to remove CH_2Cl_2 solvents and then at 70 °C for 24 h producing a yellow precipitate which was removed by filtration, washed with washed with *i*-PrOH and Et_2O, and dried to afford the title compound as a mixture of **BR(C_6H_4SMe)$_6$**·12TFA and **Zn@BR(C_6H_4SMe)$_6$**·14TFA (74:26) as a yellow solid. Yield: 282 mg, 89%. ^{1}H NMR (600 MHz, CD_3OD, 25 °C): δ 2.59 (s, 18H), 4.86 (s, 24H), 5.23 (s, 12H),

6.52 (bs, 12 H), 6.72 (d, J = 7.8 Hz, 24H), 6.76 (d, J = 7.8 Hz, 24H), 7.52 (d, J = 8.4 Hz, 12H), 8.00 (m, 24H), 8.63 (s, 12H), 8.93 (s, 12H). ^{1}H NMR data for **BR(C$_6$H$_4$SMe)$_6$·**12TFA and **Zn@BR(C$_6$H$_4$SMe)$_6$·**14TFA (600 MHz, CD_3SOCD_3, 25 °C): δ 2.59 (s, 12H), 2.61 (s, 12H), 4.78 (bs, 24H), 6.46 (bs, 12H), 6.56 (bs, 48H), 6.62 (bd, J = 6.6 Hz, 24H), 6.73 (bd, J = 6.6 Hz, 24H), 7.32 (bs, 12H), 7.54 (d, J = 8.4 Hz, 12H), 7.57 (d, J = 8.4 Hz, 12H), 7.96 (bs, 12H), 7.99 (d, J = 8.4 Hz, 12H), 8.08 (d, J = 8.4 Hz, 12H), 8.75 (s, 12H), 8.83 (s, 12H), 9.00, (s, 12H). ^{13}C NMR (150 MHz, CD_3SOCD_3, 25 °C): δ 14.1, 61.0, 109.8, 111.4, 115.3, 117.0 (q, J = 299 Hz, TFA), 120.7, 125.9, 126.2, 127.7, 129.6, 130.7, 130.7, 133.6, 143.4, 143.4, 146.9, 147.3, 149.0, 150.0, 151.2, 153.4, 153.6, 158.2 (q, J = 31.8 Hz, TFA), 160.6, 163.8, 167.4. HRMS (ESI): *m/z* 1709.3462 (20) $[M - 3CF_3CO_2]^{3+}$, 1253.6640 (100) $[M - 4CF_3CO_2]^{4+}$, 980.3720 (30) $[M - 5CF_3CO_2]^{5+}$.

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Supporting Information Available: ^{1}H NMR spectra of **BR·**12TFA and **Zn@BR·**14TFA and **BR(C$_6$H$_4$CH$_2$OAc)$_6$·**12TFA and **Zn@BR(C$_6$H$_4$CH$_2$OAc)$_6$·**14TFA. This material is available free of charge via the Internet at http://pubs.acs.org.

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