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New macrocyclic ligands having discrete metal binding sites

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Abstract—New macrocyclic dinucleating ligands have been easily synthesized by Schiff-base condensation reaction with the appropriate aldehyde and amine using the boric ion template method. The ligands have two N2O2 metal-binding sites which are doubly linked to each other with methylene spacers. The ligands chelate with Co^{2+}, Cu^{2+} and Ni^{2+} to form dimetallic compounds in high yields. © 2002 Elsevier Science Ltd. All rights reserved.

The recent growth of studies on multi-metallic compounds comes from the areas of homogeneous catalysis, magnetic exchange between paramagnetic centers, and bioinorganic chemistry.[1] There are many multi-metal center proteins and enzymes in nature; prominent among these are many with homo- and heterodinuclear metal centers.[2] Molecular systems having two or more redox active centers in close proximity, capable of cooperative interactions, are also of interest in relation to their potential as catalysts for reduction or oxidation reactions.[3] Considerable effort has thus been directed in recent years towards the synthesis of ligands capable of holding two metal ions, either the same or different, at separations which are subject to control by appropriate modification of the molecular topology.[4,5] In this study, we report the synthesis of new macrocyclic dinucleating ligands having two N2O2 metal-binding sites which are doubly linked to each other with methylene spacers as shown in Fig. 1. The structure of the compounds is designed to create discrete metal sites, and it would be expected from CPK model study that the dimetal complexes do not have a distorted structure.

The ligand **1** was prepared by the method, in which a boric ion was used as a template as shown in Scheme 1. To a solution of 3,3′-methylenebis(salicylaldehyde) (95.7 mg, 0.26 mmol) in 2 mL of $CHCl_3$ was added a boric acid (8.0 mg, 0.13 mmol) in 2 mL of methanol and stirred for 30 min at room temperature. Then a methanol solution of *o*-phenylenediamine (28.1 mg, 0.26 mmol) was added and yellow precipitation appeared during stirring for 1 h. The precipitates were collected by filtration, washed by methanol and dried in vacuo. The precipitated solid gave satisfactory elemental analyses without further purification. Neither the metal-templated method, such as Ni^{2+} and La^{3+}, nor the high dilution method formed the pure desired product, while the compounds obtained from these methods included 2:2 condensation products as deduced from mass spectroscopic analysis (MALDI-TOF). The utility of this boric ion-templated method has been reported by Pierre et al.[5] They considered that phenolate is covalently coordinated to boron to form hypothetical intermediates.[†]

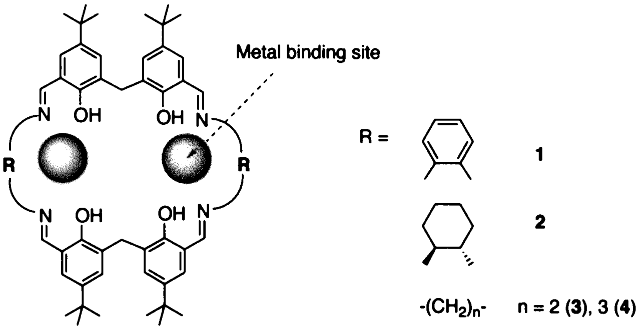

Figure 1. Schematic representation of the macrocyclic dinucleating ligands.

Keywords: macrocyclic ligand; Schiff-base; cobalt complex; X-ray crystallography; redox behavior.

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[†] When we used *p*-toluenesulfonic acid in place of boric acid, the formation of ligand **1** did not proceed effectively. Therefore, we expected that a boric ion acted as a template under the reaction conditions.

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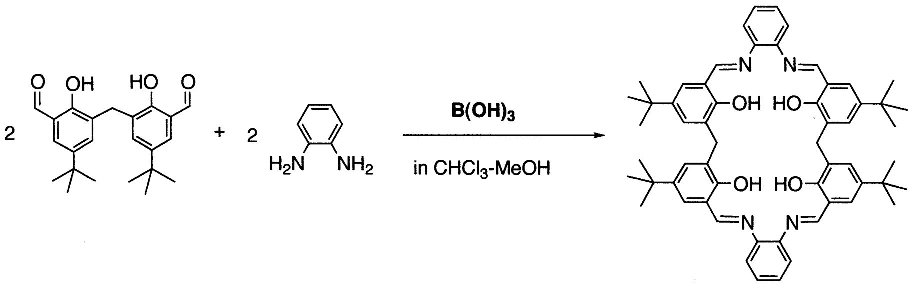

Scheme 1.

The structure of **1** was identified by ^{1}H NMR, MALDI-TOF MS and X-ray crystallographic analysis.[‡] Due to the symmetry of the ligand, ^{1}H NMR spectroscopy reveals four singlets corresponding to the 36 methyl protons (δ 1.25 ppm), the four protons of the two bridging methylene (δ 4.19 ppm), the four imine protons (δ 8.64 ppm), and the four phenol protons (δ 13.27 ppm), respectively, as well as pairs of two aromatic protons doublets (δ 7.17 and 7.23 ppm, $J=2$ Hz) and multiplets (δ 7.29 and 7.31 ppm). The spectrum did not change over 1 month due to the appropriate methylene spacers linked to the *ortho*-position of each phenol moiety which relaxes the tension of the cyclic structure; thus, **1** has high stability in solution. The X-ray analysis of **1**, in fact, shows that it has a macrocyclic structure and has two N2O2 metal binding sites as shown in Fig. 2.[§] Other ligands **2**, **3** and **4** were also synthesized in the same manner as for **1** except for the use of the corresponding diamine in place of *o*-phenylenediamine.[‡]

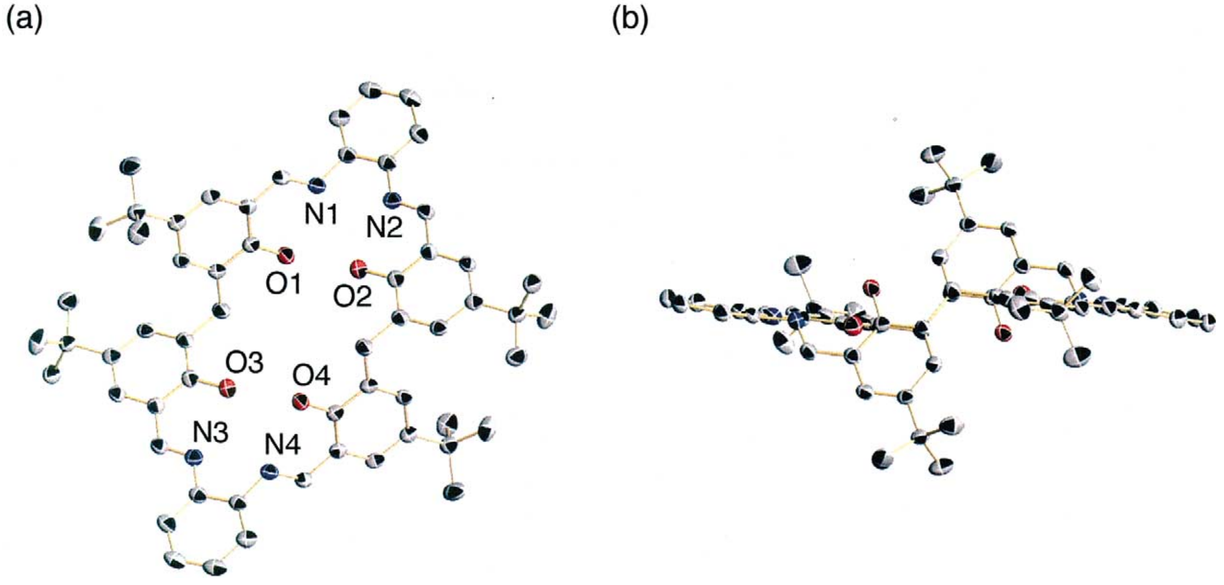

Figure 2. ORTEP drawing of **1** with thermal ellipsoids at 50% probability. (a) Top view, (b) side view. Hydrogen atoms have been omitted for clarity.

[‡] Compound **1**: yield 88%; ^{1}H NMR (CDCl$_3$, 500 MHz): $\delta=1.25$ [s, 36H, C$\underline{H}_3$], 4.19 [s, 4H, -C$\underline{H}_2$-], 7.17 [d, 4H, Ph], 7.23 [d, 4H, Ph], 7.29 [m, 4H, Ph], 7.31 [m, 4H, Ph], 8.64 [s, 4H, N=C$\underline{H}$], 13.27 [br, 4H, O$\underline{H}$]; MALDI-TOF MS (dithranol matrix): *m*/*z* 880.6 (M^+). Anal. found: C, 78.81; H, 7.29; N, 6.30%. Calcd for $C_{58}H_{64}N_4O_4$: C, 79.06; H, 7.32; N, 6.36%. Compound **2**: yield 89%; ^{1}H NMR (CDCl$_3$, 500 MHz): $\delta=1.13$ [s, 36H, C$\underline{H}_3$], 1.41–1.82 [m, 16H, -cycloC$\underline{H}_2$-], 3.26 [d, 4H, -C=N-C$\underline{H}$-], 3.97 [m, 4H, -C$\underline{H}_2$-], 6.95 [dd, 4H, Ph], 7.13 [dd, 4H, Ph], 8.22 [m, 4H, N=C$\underline{H}$], 13.44 [br, 4H, O$\underline{H}$]; MALDI-TOF MS (dithranol matrix): *m*/*z* 894.4 (M^++1). Anal. found: C, 77.54; H, 8.53; N, 6.08%. Calcd for $C_{58}H_{76}N_4O_4$: C, 77.99; H, 8.58; N, 6.27%. Compound **3**: yield 88%; ^{1}H NMR (CDCl$_3$, 500 MHz): $\delta=1.18$ [s, 36H, C$\underline{H}_3$], 3.87 [s, 8H, -C$\underline{H}_2$C$\underline{H}_2$-], 4.02 [s, 4H, -C$\underline{H}_2$-], 7.03 [d, 4H, Ph], 7.22 [d, 4H, Ph], 8.32 [s, 4H, N=C$\underline{H}$], 13.27 [br, 4H, O$\underline{H}$]; MALDI-TOF MS (dithranol matrix): *m*/*z* 785.5 (M^++1). Anal. found: C, 76.20; H, 8.21; N, 7.02%. Calcd for $C_{50}H_{64}N_4O_4$: C, 76.49; H, 8.22; N, 7.14%. Compound **4**: yield 90%; ^{1}H NMR (CDCl$_3$, 500 MHz): $\delta=1.22$ [s, 36H, C$\underline{H}_3$], 2.05 [m, 4H, -CH$_2$C$\underline{H}_2$CH$_2$-], 3.66 [t, 8H, -C$\underline{H}_2$CH$_2$C$\underline{H}_2$-], 4.08 [s, 4H, -C$\underline{H}_2$-], 7.07 [d, 4H, Ph], 7.31 [d, 4H, Ph], 8.34 [s, 4H, N=C$\underline{H}$], 13.52 [br, 4H, O$\underline{H}$]; MALDI-TOF MS (dithranol matrix): *m*/*z* 814.0 (M^++1). Anal. found: C, 76.69; H, 8.44; N, 6.62%. Calcd for $C_{52}H_{68}N_4O_4$: C, 76.81; H, 8.43; N, 6.89%.

[§] Vapor diffusion of Et$_2$O into the CHCl$_3$ solution of **1** afforded pale yellow crystals. Crystal data for **1**·H$_2$O: $C_{58}H_{66}N_4O_5$, $M_w=899.15$, crystal system=triclinic, space group=$P\bar{1}$, $Z=1$ in a cell with the following dimensions: $a=10.1173(7)$, $b=11.8749(9)$, $c=12.9935(9)$ Å, $\alpha=114.8610(10)$, $\beta=92.661(2)$, $\gamma=113.781(2)°$, $V=1251.53(15)$ Å^3, $D_{\text{calcd}}=1.193$ g cm^{-3}. The data were collected at 173 K on a Bruker SMART APEX CCD diffractometer, λ (Mo Kα)=0.71073 Å, $\mu=0.076$ mm^{-1}, 8187 measured and 5096 unique reflections ($2\theta_{\max}=52.74$, $R_{\text{int}}=0.0157$). $R=0.0581$, $R_w=0.1697$. Crystallographic data for the structure in this paper has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 183252 (**1**).

The coordination behavior of these ligands was investigated as follows. The ligand **1** chelates with various transition metal ions such as Co^{2+}, Cu^{2+} and Ni^{2+} to form a dinuclear metal complex in high yield.[¶] General procedure for the synthesis of dimetal complex is described below. To a solution of **1** (47.6 mg, 0.054 mmol) in 5 mL of chloroform was dropwise added $Co(OAc)_2 \cdot 4H_2O$ (27.4 mg, 0.11 mmol) in 5 mL of methanol under nitrogen atmosphere. After the solution changed to brown color, it was stirred for 1 h at room temperature. The solvent was removed by evaporation to give a brown solid, and then washed with methanol and dried in vacuo. The corresponding dinickel and dicopper complexes were obtained in a similar manner.

The complexes have discrete metal sites, so that similar electronic spectra and electrochemical data were obtained for the dimetal complexes and the corresponding monometal complexes. Cyclic voltammograms of the dicobalt complex **5** and the corresponding mononuclear cobalt complex **8** in DMF are shown in Fig. 3. The $Co^{II}Co^{II}/Co^{I}Co^{I}$ and $Co^{III}Co^{III}/Co^{II}Co^{II}$ for the complex **5** were observed at −1.10 V and +0.10 V versus Ag/AgCl, respectively. These redox potentials are similar to those for the corresponding monocobalt complex **8**, which are observed at −1.20 V for Co^{II}/Co^{I} and +0.20 V versus Ag/AgCl for Co^{III}/Co^{II}, respectively.[‖]

In conclusion, new dinucleating ligands with a macrocyclic structure have been synthesized by a convenient method. The ligands have two discrete N2O2 metal binding sites and formed dimetal complexes. Such dimetal complexes can activate two molecules at the same time to form a pair of active species.[6] Detailed properties and reactivities of the dimetal complexes are now under investigation in our laboratory.

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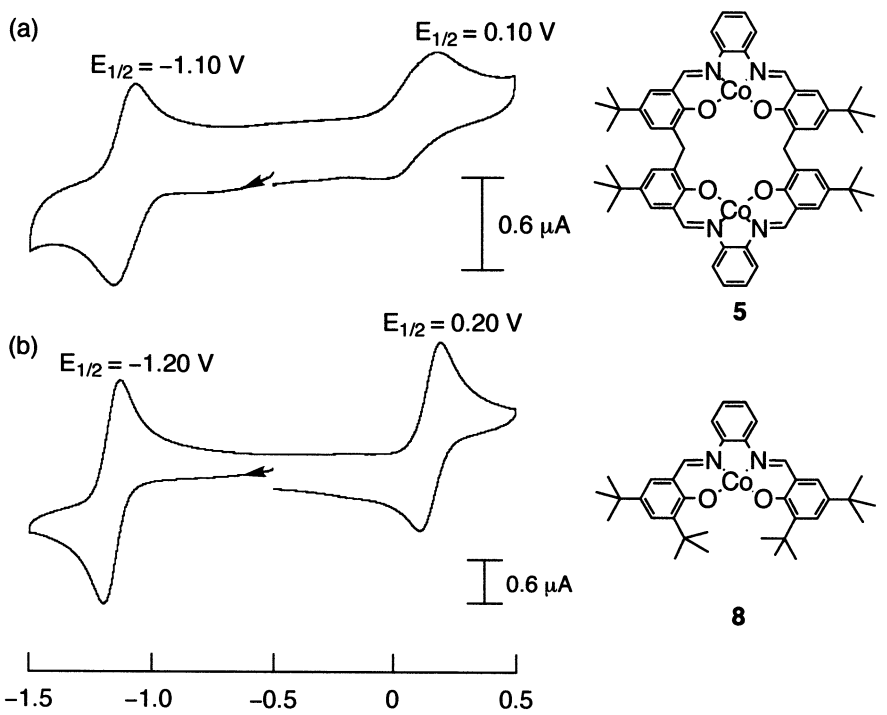

Figure 3. Cyclic voltammograms of the cobalt complexes in DMF containing 0.1 M NBu_4ClO_4. Scan rate 100 mV s^{-1}. (a) The dinuclear complex **5**, 5.0×10^{-4} M. (b) The mononuclear complex **8**, 1.0×10^{-3} M.

[¶] **5** ($Co^{II}Co^{II}$): yield 84%; HRMS (FAB, *m/z*): calcd for $C_{58}H_{61}Co_2N_4O_4$: $[MH]^+$, 995.3357. Found: $[MH]^+$, 995.3328. **6** ($Cu^{II}Cu^{II}$): yield 95%; HRMS (FAB, *m/z*): calcd for $C_{58}H_{61}N_4Cu_2O_4$: $[MH]^+$, 1003.3485. Found: $[MH]^+$, 1003.3146. **7** ($Ni^{II}Ni^{II}$): yield 89%; ^1H NMR ($CDCl_3$, 500 MHz): $\delta = 1.27$ [s, 36H, $C\underline{H}_3$], 4.42 [s, 4H, $-C\underline{H}_2-$], 7.10 [d, 4H, Ph], 7.19 [dd, 4H, Ph], 7.37 [d, 4H, Ph], 7.66 [dd, 4H, Ph], 8.20 [s, 4H, $N{=}C\underline{H}$]; HRMS (FAB, *m/z*): calcd for $C_{58}H_{61}N_4Ni_2O_4$: $[MH]^+$, 993.3400. Found: $[MH]^+$, 993.3403.

[‖] The monocobalt(II) complex **8** was synthesized by the condensation of *o*-phenylendiamine and 3,5-di-*t*-butylsalicylaldehyde and subsequent reaction with $Co(OAc) \cdot 4H_2O$. Yield 40%; MALDI-TOF MS (dithranol matrix): *m/z* 597.7 (M^+). The redox behavior suggests that the dicobalt complex **5** has two discrete square planar structures in analogy with the mononuclear cobalt complex **8**, although the two N2O2 metal binding sites of the ligand **1** are not on the same plane in the crystal state.

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