as found for the monofunctional salts, i.e., the two heterocyclic rings are noninteracting. Characterization of the neutral species obtained by reduction of these dications is in progress.

Acknowledgment. We thank the Natural Sciences and Engineering Research Council of Canada, the National Science Foundation (EPSCOR program), and the State of Arkansas for financial support.

Supplementary Material Available: Tables of crystallographic data (S1), atomic coordinates (S2 and S3), bond lengths and angles (S4 and S5), and anisotropic thermal parameters (S6 and S7) for $[PhCN_2Se_2]^+PF_6^-{\cdot}PhCN$ and $[PhCN_2Se_2]_2$ (11 pages); tables of observed and calculated structure factors (S8 and S9) for $[PhCN_2Se_2]^+PF_6^-{\cdot}PhCN$ and $[PhCN_2Se_2]_2$ (24 pages). Ordering information is given on any current masthead page.

(Template)^2 Synthesis of a Dinucleating Macrocyclic Ligand and Crystal Structure of Its Dicopper(II) Imidazolate Complex

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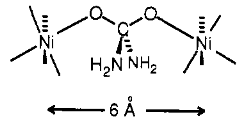
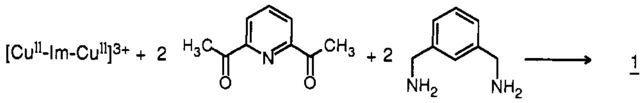
Received July 18, 1989

Mimicry of metalloprotein active sites lends insight toward structure-function relationships in biological systems as well as the development of abiotic catalysts. Reaction centers containing two or more transition-metal ions are of particular interest in studying the cooperative effects of redox-active or Lewis acid sites.[2] In these systems, synthetic macrocyclic ligands offer a convenient means of preorganization of ligands for controlling both metal ion and auxiliary ligand or substrate binding.[3] Dinuclear complexes as mimics of the nickel-containing enzyme urease would aid in deciphering the features that give rise to a 10^{14} rate acceleration in urea hydrolysis.[4] Here we report the design, synthesis, and characterization of dicopper(II) and dinickel(II) macrocyclic complexes as a first step toward this goal.

Recent magnetic measurements by Wilcox[5] indicate that urease has a dinuclear Ni^{II} center with weak antiferromagnetic coupling between the two distorted O_h sites due to a bridging ligand and also suggest coordination of bridging substrates. A proposed mechanism involves binding of both urea and H_2O between the metal ions, leading to a carbon tetrahedral intermediate with a three-atom bridge (O-C-O) spanning the metal centers.[6] One arrangement of the relevant players would place the nickel ions at an internuclear separation of nearly 6 Å.[7]



In order to construct a mimic of the urease active site, we sought a semirigid macrocyclic framework that would allow coordination of two Ni^{II} ions in a nearly octahedral geometry with a three-atom separation for a bridging substrate (or intermediate). In this strategy, the N-C-N portion of imidazolate served as a mimic of the desired O-C-O spacer. The well-known propensity for formation of μ-bridged imidazolate complexes of Cu^{II}[9] (and more rarely Ni^{II})[10] led us to postulate the use of the Cu-Im-Cu (or Ni-Im-Ni) moiety in the template synthesis of the macrocyclic complex $[LCu_2(\mu\text{-Im})](CF_3SO_3)_3{\cdot}H_2O$ (**1**). To our knowledge, this is the first use of a simple dinuclear metal unit as a template for macrocyclization. We have termed this reaction a (template)^2 synthesis to reflect the role of imidazolate in first defining the metal-metal distance, which subsequently results in organization and condensation of the Schiff base macrocycle around the secondary template,[11] according to the following reaction:



The synthetic procedure consisted of addition of equimolar amounts of $Cu(CF_3SO_3)_2$ and imidazole in CH_3OH to an equimolar solution of 2,6-diacetylpyridine and *m*-xylylenediamine in CH_3OH. After 12 h at room temperature, a green precipitate was isolated in 82% yield and characterized.[12] Recrystallization from propylene carbonate and THF yielded crystals suitable for X-ray crystallographic analysis. Substituting nickel in place of copper led to the formation of a yellow solid, proposed to be an analogous complex, $[LNi_2(\mu\text{-Im})](NO_3)_3{\cdot}5H_2O$.[13] The usual method of synthesis of dinucleating Schiff base macrocycles entails the use of a single large metal ion template such as Pb^{2+}, Sr^{2+}, Ba^{2+}, or Ag^+,[14] which, in our system, failed to give soluble nonpolymeric products; the rigidity of the *m*-xylyl groups is, in fact, likely to prevent templation around a single metal ion. Furthermore, it is important to note that Cu^{2+} or Ni^{2+} ions in the *absence* of imidazole were ineffective toward macrocyclization.[15]

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(7) Alternatively, Buchanan et al.[8] have proposed substrate bridging between two apical positions in a Ni_2 model complex with a Ni-Ni separation of 3.42 Å.

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(11) The precise sequence of template formation cannot be well-defined; however, it is certain that two Cu^{2+} and one Im^- are required in the cavity before final ring closure may occur.

(12) $[LCu_2(\mu\text{-Im})](CF_3SO_3)_3{\cdot}H_2O$ (82% yield): IR (KBr pellet) ν 1631 (m, C=N), 1596 (m, phenyl), 1476 (m, pyridine), 3460 (s, OH), 1278 (s, $(SO_3)_{as}$, ionic $CF_3SO_3^-$), 1248 (s, $(SO_3)_{as}$, bound $CF_3SO_3^-$) cm^{-1}. Anal. Calcd for $C_{40}H_{39}N_8O_9S_3F_9Cu_2$: C, 40.50; H, 3.31; N, 9.45; Cu, 10.71. Found: C, 40.10; H, 3.39; N, 9.15; Cu, 10.46.

(13) The compound analyzed correctly for the formula $[LNi_2(\mu\text{-Im})](NO_3)_3{\cdot}5H_2O$. Anal. Calcd for $C_{37}H_{47}N_{11}O_{14}Ni_2$: C, 45.27; H, 4.87; N, 15.88. Found: C, 45.01; H, 4.80; N, 15.61.

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(15) Extensive attempts made in the *absence* of imidazole gave reproducibly poor yields. Specifically, extraction of copper from the reaction mixture with EDTA as described below[19] yielded mainly unidentified polymeric species; analysis by ^1H NMR of the organic material taken up in CH_2Cl_2 indicated that the macrocycle was formed in less than 5% yield, and the diacetylpyridine could be recovered in 15% yield.

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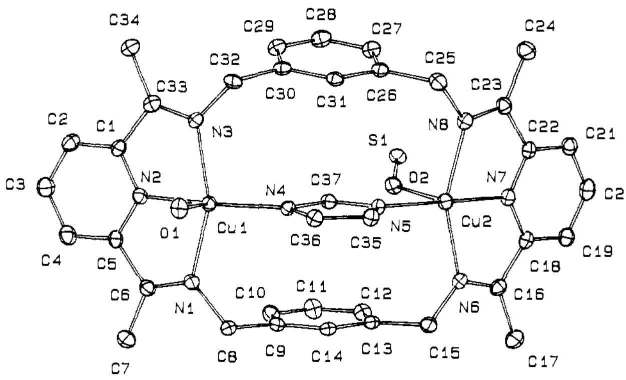

Figure 1. ORTEP drawing of **1**·3THF showing the 50% probability thermal ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond distances (angstroms) and angles (degrees) are as follows: Cu1···Cu2, 5.9181 (9); Cu1–N1, 2.070 (3); Cu1–N2, 1.928 (4); Cu1–N3, 2.073 (3); Cu1–N4, 1.960 (4); Cu1–O1, 2.248 (2); Cu2–N5, 1.945 (3); Cu2–N6, 2.084 (3); Cu2–N7, 1.929 (4); Cu2–N8, 2.066 (3); Cu2–O2, 2.442 (3); Cu2···O9, 2.724 (4); N1–Cu1–N2, 78.4 (1); N1–Cu1–N3, 156.7 (1); N1–Cu1–N4, 101.4 (1); N2–Cu1–N3, 78.4 (1); N2–Cu1–N4, 165.0 (1); N3–Cu1–N4, 100.9 (1); N1–Cu1–O1, 95.9 (1); N2–Cu1–O1, 98.4 (1); N7–Cu2–N8, 78.8 (1); N6–Cu2–N8, 155.7 (2); N5–Cu2–N8, 102.4 (1); N6–Cu2–N7, 78.5 (1); N5–Cu2–N7, 177.7 (1); N5–Cu2–N6, 100.5 (1); Cu1–N4–C37, 128.9 (3); Cu2–N5–C37, 126.5 (2).

Supporting evidence for the involvement of the Cu–Im–Cu moiety in the macrocycle synthesis was obtained from a solution ESR study. The spectrum of a methanol solution of copper triflate and imidazole in a 1:1 ratio (at a 2.5×10^{-1} M concentration, corresponding to that used for the synthesis of **1**) showed a broad resonance at $g = 2.174$ with features characteristic of a dipole–dipole interaction. That such a phenomenon still existed after a 100-fold dilution indicates that aggregates are excluded; therefore, it can only be explained by the presence of a bridged dinuclear species, most likely the imidazolate, existing in solution prior to the formation of the macrocycle.

In the structure[16] of **1**·3THF (Figure 1), each copper atom possesses a square planar N_4 environment forming a dinuclear unit through a bridged imidazolate. The axial positions to the N_4 planes are occupied for one copper by a ligand H_2O (Cu1–O1 = 2.248 (2) Å) while, for the other copper, two oxygen atoms of two triflate anions lie in a trans position, one weakly bound (Cu2–O2 = 2.442 (3) Å and the other (not represented) further away (Cu2···O9 = 2.724 (4) Å). The benzene and imidazolate rings are nearly coplanar whereas the two pyridine rings are oriented at an angle of 123.0 (2)°. This angle as well as a Cu–Cu separation of 5.92 Å suggests that a tetrahedral intermediate such as $(H_2N)_2C(O^-)_2$ could replace imidazolate as a bridging ligand in catalytic hydrolysis.

The electronic spectrum of **1** in propylene carbonate displayed absorption bands at 694 ($\epsilon = 270$ M^{-1} cm^{-1}) and 294 nm ($\epsilon = 8700$ M^{-1} cm^{-1}), which arise respectively from a d–d transition and from an L → Cu^{II} charge-transfer band. More importantly, the ESR spectrum of **1** (solid state, room temperature) provided clear evidence for an antiferromagnetic exchange interaction: this is supported by the detectable $\Delta M = 2$ transition at $g = 4.29$ as already observed in other $Cu_2(\mu\text{-Im})$ complexes.[17] The electrochemical studies in propylene carbonate showed a quasi-reversible reduction corresponding to the transfer of two electrons at $E_{1/2} = -435$ mV (scan rate, 50 mV s^{-1}) confirming, as already suggested,[18] that the size of the macrocycle is of importance for the observation of a single reduction process $Cu_2^{II} \rightarrow Cu_2^{I}$.

The free ligand L could be obtained in 72% yield by extraction of the metal ions (copper and alternatively nickel) from complex **1** with EDTA.[19] Complete characterization of L has been carried out by the usual methods (microanalysis, IR, FAB$^+$-MS), and strong evidence has been obtained for the presence of both unprotonated and monoprotonated forms in a 3:2 ratio, as supported by the ^{1}H NMR analysis in CD_2Cl_2. As a tetraimine, L is unstable for extended periods in aqueous solution but may be handled as a solid or in nonaqueous solvents. Furthermore, complex **1** could be regenerated by addition of 2 equiv of Cu^{2+} to L in the presence of ImH (1 equiv).

In summary, a novel method of templated macrocyclization has been discovered leading to both dicopper and dinickel complexes which should be well-constructed for catalysis of urea hydrolysis and related substrates. Studies directed toward this goal are in progress.

Acknowledgment. This research was supported by a grant from the National Institutes of Health (GM-34841) to C.J.B. and a NATO Collaborative Research Grant to C.J.B. and M.-T.Y. M.-T.Y. also thanks the Centre National de la Recherche Scientifique for additional support.

Supplementary Material Available: Tables of atomic coordinates, bond lengths and angles, anisotropic thermal parameters, and hydrogen atom coordinates (15 pages); table of observed and calculated structure factors (26 pages). Ordering information is given on any current masthead page.

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(16) $[LCu_2(\mu\text{-Im})](CF_3SO_3)_3{\cdot}H_2O{\cdot}3C_4H_8O$ ($C_{52}H_{63}N_8O_{13}S_3F_9Cu_2$, MW = 1402.39) crystallizes in the triclinic space group $P\bar{1}$ with $a = 18.016$ (6) Å, $b = 18.287$ (6) Å, $c = 9.704$ (4) Å, $\alpha = 99.99$ (2)°, $\beta = 92.74$ (2)°, $\gamma = 73.79$ (2)°, $V = 3023$ Å^3, $Z = 2$, $\rho_{calcd} = 1.540$ g/cm^3. A crystal of **1**·3THF was selected in its mother liquor, deposited onto a cooled plate, and transferred above a liquid nitrogen bath to a goniostat, where it was cooled to −100 °C. All the data were collected on a Philips PW 1100/16 diffractometer at −100 °C equipped with a low-temperature self-built device. Of the 8947 unique data collected with Cu Kα radiation ($\lambda = 1.5418$ Å), the 6838 with $I > 3\sigma(I)$ were used in the least-squares refinement, to yield $R = 4.6\%$, $R_w = 6.9\%$.

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(19) The extraction was carried out by treating a 30 mM solution in **1** in CH_3CN with a 5-fold (by volume) amount of 50 mM Na_4EDTA. After 45 min, a tan precipitate of macrocycle L was isolated, washed with CH_3CN, and analyzed: IR (KBr pellet) ν 1635 (m, C=N), 1565 (m, phenyl), 1442 (m, pyridine), 1260 (w, $(SO_3)_{as}$, anionic $CF_3SO_3^-$), 3275 (NH) cm^{-1}; ^{1}H NMR (200 MHz, CD_2Cl_2) δ 8.5–7.2 (m, 14 H, aromatic), 6.72 (s, 0.4 H, NH), 4.89 and 4.78 (3:2 ratio, s, 8 H, benzylic), 2.53 and 2.27 ppm (2:3 ratio, 12 H, CH_3); FAB$^+$-MS, $m/z = 527.4$ (expected value for $(M + H)^+$ at 527.3). Anal. Calcd for 60% $C_{34}H_{34}N_6$ and 40% $C_{34}H_{34}N_6{\cdot}CF_3SO_3H$: C, 70.42; H, 5.91; N, 14.32. Found: C, 69.61; H, 6.04; N, 13.99.