reactivity of these Pt(II) ions can be influenced by other factors. The H-bonding ability of the amine ligands does not, however, markedly contribute to the kinetics. The reactivity of purine nucleosides appears to depend drastically on the substituent at C6 of the purine ring, i.e. O > H > NH_2. The oxo subsitutent enhancement of the reaction rate can be attributed to the formation of an H-bond from the coordinated water molecule to C6O in both steps, whereas the amino group at C6 sterically prevents the attack of Pt(II).

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Registry No. *cis*-$[Pt(NH_3)(H_2O)_2]^{2+}$, 20115-64-4; *cis*-$[Pt(NH_3)CH_3NH_2(H_2O)_2]^{2+}$, 52241-28-8; *cis*-$[Pt(NH_3)(CH_3)_2NH(H_2O)_2]^{2+}$, 52241-30-2; $[Pt(tmen)(H_2O)_2]^{2+}$, 74765-29-0; adenosine, 58-61-7; guanosine, 118-00-3; 1-methylguanosine, 2140-65-0; inosine, 58-63-9; 1-methylinosine, 2140-73-0; 9-(β-D-ribofuranosyl)purine, 550-33-4.

Supplementary Material Available: A listing of temperature-dependent rate data for Pt(II) 1:1 complexes of Guo and Puo (1 page). Ordering information is given on any current masthead page.

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Copper(I) Hemocyanin Models: Variable Coordination Number and Distorted Geometries in Benzimidazole Chelates

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Dinuclear copper(I) complexes derived from three benzimidazole-containing binucleating ligands are described within the context of synthetic models for deoxyhemocyanin and carbon monoxyhemocyanin. The neutral, potentially septadentate ligand HL-Et, which contains bis((1-ethyl-2-benzimidazolyl)methyl) moieties at both ends of a 2-hydroxypropylenediamine spacer, forms the CO complex $[Cu_2(HL\text{-}Et)(CO)_2][CF_3SO_3]_2$ (**1**) and the acetonitrile complex $[Cu_2(HL\text{-}Et)(MeCN)_2][CF_3SO_3]_2$ (**2**). The related tetrakis(1-methylbenzimidazole)-containing ligand HCAB-Me, having a 2,6-disubstituted cresol spacer, forms the acetonitrile complex $[Cu_2(HCAB\text{-}Me)(MeCN)_2][CF_3SO_3]_2$ (**3**). The unalkylated benzimidazole analogue of HL-Et, HL-H, forms the acetonitrile complex $[Cu_2(HL\text{-}H)(MeCN)_2][ClO_4]_2 \cdot {}^1/_3Et_2O$ (**4**) and the CO complex $[Cu_2(HL\text{-}H)(CO)_2][BF_4]_2$ (**5**). Complexes **1**-**4** have been characterized by X-ray crystallography. All complexes reveal an approximately trigonal array of two benzimidazoles and the added ligand (CO or MeCN) along with a widely varying apical interaction with the tertiary amine N atom. The unusual feature of these nominally four-coordinate trigonal-pyramidal species **1**-**3** is the large off-normal distortion that is observed in the apical copper-amine bond as it spans the range 2.31-2.73 Å. In complex **4** the off-normal pulling away of the tertiary amine is complete and three-coordination prevails. These complexes further extend the plasticity of coordination number and geometry seen in copper(I) complexes. The superior ligand-constraining ability of proteins suggests that highly irregular coordinate geometries will be the rule rather than the exception in copper proteins. Crystal data: **1**, $C_{47}H_{50}N_{10}O_9Cu_2F_6S_2$, triclinic, $P\bar{1}$, a = 16.616 (8) Å, b = 11.884 (5) Å, c = 15.131 (4) Å, α = 106.69 (3)°, β = 83.25 (3)°, γ = 110.75 (4)°, Z = 2; **2**, $C_{49}H_{56}N_{12}O_7Cu_2F_6S_2$, orthorhombic, *Pbcn*, a = 15.473 (5) Å, b = 16.369 (9) Å, c = 44.178 (17) Å, Z = 8; **3**, $C_{51}H_{51}O_7Cu_2F_6S_2$, triclinic, $P\bar{1}$, a = 14.20 (1) Å, b = 13.39 (1) Å, c = 15.31 (1) Å, α = 104.52 (6)°, β = 76.08 (7)°, γ = 90.71 (8)°, Z = 2; **4**, $C_{39}H_{40}N_{12}O_9Cu_2Cl_2 \cdot {}^1/_3C_4H_{10}O$, monoclinic, $C2/c$, a = 28.710 (9) Å, b = 7.600 (2) Å, c = 21.857 (9) Å, β = 114.23 (3)°. Benzimidazole Cu-N distances for **1**-**4** all lie within the range 1.96-2.03 (1) Å. Cu-C distances in **1** are 1.82 (2) and 1.77 (2) Å at Cu1 and Cu2, respectively. Acetonitrile Cu-N distances lie within the range 1.87-1.96 (1) Å for complexes **2**-**4**.

Copper proteins present interesting problems of structure for the copper(I) oxidation state. They are difficult to probe in detail, and what we do know of them suggests they are rarely regular or predictable. The most accurately determined structure to date is that of the type I blue copper protein plastocyanin from *Populus nigra*.[3] The copper(I) coordination sphere is made up of three strongly binding ligands (His, His, Cys) and a weak interaction at 2.9 Å with methionine. The stereochemistry is sufficiently far from ideality that describing it in terms of a distorted tetrahedron that is tending toward an elongated trigonal pyramid has rather limited utility. Other proteins with mononuclear copper active sites such as superoxide dismutase have so far been structurally characterized only in the copper(II) oxidation state.[4] In the only reported crystal structure of a copper(I) protein with an active site of the dinuclear type, that of *Panulirus interruptus* hemocyanin at moderate resolution, coordination by three histidines is indicated.[5] The Cu···Cu separation is 3.7 (3) Å. That EXAFS results have been interpreted in terms of two-[6] or three-coordination[7] suggests either site asymmetry or site irregularity, perhaps because one histidine is coordinated more weakly than the other two. It should also be remembered that hemocyanin shows cooperativity of dioxygen binding (but not CO binding), a phenomenon that is probably triggered by the structural changes attendant with the oxidation-state change that results from dioxygen binding.[8] A geometrical compromise between the quite different intrinsic structural preferences of copper(I) and copper(II) is therefore quite possible in one or both of the oxy and deoxy forms. There is also the unresolved issue of H_2O (or OH^-) molecules at the active site. An OH^- ligand (referred to as the endogenous bridge) is strongly implicated in copper(II) forms of hemocyanin[9] and related dinuclear copper proteins.[10] In the copper(I) form, water associated with the active site might go unnoticed in the crystal structure and weak coordination would be difficult to detect in XANES or EXAFS studies. Carbon monoxide binding to hemocyanin presents a further intriguing structural problem for copper(I). Since a single terminal CO molecule binds to one of the two approximately equivalent copper atoms,[11] there must be some sort of electronic or steric control

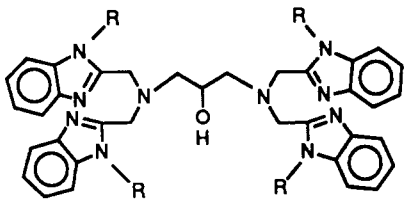
(1) University of Southern California.
(2) University of Canterbury.
(3) Guss, J. M.; Harrowell, P. R.; Murata, M.; Norris, V. A.; Freeman, H. C. *J. Mol. Biol.* **1986**, *192*, 361.
(4) Tainer, J. A.; Getzoff, E. D.; Beem, K. M.; Richardson, J. S.; Richardson, D. C. *J. Mol. Biol.* **1982**, *160*, 181.
(5) Gaykema, W. P. J.; Volbeda, A.; Hol, W. G. *J. Mol. Biol.* **1985**, *187*, 255.
(6) Co, M. S.; Scott, R. A.; Hodgson, K. O. *J. Am. Chem. Soc.* **1981**, *103*, 986.
(7) Brown, J. M.; Powers, L.; Kincaid, B.; Larrabee, J. A.; Spiro, T. G. *J. Am. Chem. Soc.* **1980**, *102*, 4210.
(8) Reed, C. A. In *Biological & Inorganic Copper Chemistry*; Karlin, K. D., Zubieta, J., Eds.; Adenine: New Yor, 1986; Vol. I, p 61.
(9) Wilcox, D. E.; Long, J. A.; Solomon, E. I. *J. Am. Chem. Soc.* **1984**, *106*, 2186.
(10) Spira-Solomon, D. J.; Solomon, E. I. *J. Am. Chem. Soc.* **1987**, *109*, 6421.

0020-1669/90/1329-0110$02.50/0

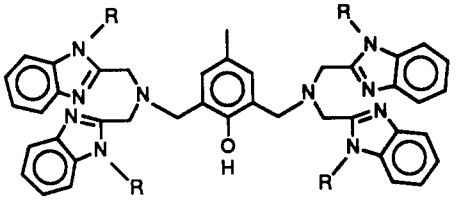
of coordination number. The negligible[12] or low[13] affinity of two-coordinate copper(I) for CO, relative to that of three-coordinate complexes, has in the past formed the basis of an electronic explanation.[12] However, steric congestion (or a constrained three-coordinate geometry at one copper atom, or even the presence of pseudo four-coordination from semicoordinated histidine and water) seems a more likely explanation.

All of these observations show the need for a body of knowledge on the structure of copper(I) model complexes. Of particular interest are complexes that are binuclear and that involve two or three imidazole (or imidazole-like) ligands, a potential oxygen donor ligand, a possible weak ligand, and/or carbon monoxide. Coordinate geometries and coordination numbers that are far removed from ideality are also of particular interest, as is the presence of "semicoordination", i.e. ligands with abnormally long bond distances to copper. We have previously studied the structural consequences of a third donor atom in bis(benzimidazole) complexes,[14] and there is now a reasonable body of knowledge that deals with the linear to T-shaped to trigonal progression of geometries.[15] Less is known about the distorted geometries between idealized three- and four-coordination. The number of structures of three- or four-coordinate dinuclear copper(I) model complexes has begun to grow in recent years.[16-21] In the present work we show how chelating ligand constraints can induce markedly nonidealized geometries in a compromise between three- and four-coordination. It is also evident that the balance between three- and four-coordination can be a delicate one. This is leading us to the expectation that for the electronically rather undemanding d^{10} copper(I) ion almost anything may be possible geometrically, in proteins and in complexes, provided that ligand constraints and charge effects can be controlled.

In this work we use tetrabenzimidazole binucleating ligands such as HL-H and HL-Et[22] and one of its newly synthesized close relatives, HCAB-Me.[23] The ligand HL-Et has in the past led to very successful models for copper(II) forms of hemocyanin,[22] particularly the azide,[24] and is currently finding application to the bioinorganic chemistry of manganese[25] and iron.[26]



HL-R (R = H, Et)



HCAB-R (R = Me)

Experimental Section

The ligands HL-H and HL-Et[22] and HCAB-Me[23] were synthesized as previously described. $[Cu(MeCN)_4]BF_4$,[27] $[Cu(MeCN)_4]ClO_4$,[28] and $[Cu(CH_3CN)_4]CF_3SO_3$[27] were prepared by literature methods and recrystallized to analytical purity. Methanol was triply distilled from $Mg(OMe)_2$ twice under nitrogen and finally under helium in an inert-atmosphere box. Acetonitrile was obtained from Burdick and Jackson (0.005% H_2O). When necessary, it was dried with CaH_2. Where possible, manipulations were carried out in a Vacuum Atmospheres HE-40/2 inert-atmosphere box under helium (O_2, H_2O < 1 ppm). Carbon monoxide work was performed with Schlenkware, cannula, and glovebag techniques. Infrared spectra were recorded anaerobically on a Perkin-Elmer 281 spectrometer as KBr disks prepared under an inert atmosphere or, in the case of CO complexes, under a CO atmosphere. Elemental analyses were performed by Chemical Analytical Services, Berkeley, CA.

$[Cu_2(HL\text{-}Et)(CO)_2][CF_3SO_3]_2$ (1). Methanol (5 mL) was added to a mixture of HL-Et (0.100 g, 0.138 mmol) and $[Cu(MeCN)_4]CF_3SO_3$ (0.104 g, 0.276 mmol) in a Schlenk flask inside the glovebox. The white solids dissolved quickly, giving rise to an orange-red solution. The Schlenk flask was quickly removed from the glovebox and flushed with carbon monoxide for 5 min. When it stood overnight, the solution gradually became colorless and deposited colorless crystals of X-ray quality. The mother liquor was removed, and the crystals were collected, dried, and manipulated under a CO atmosphere (yield 0.05 g, 30%). Anal. Calcd for $C_{47}H_{50}Cu_2N_{10}O_9F_6S_2$: C, 46.88; H, 4.19; N, 11.63; Cu, 10.55. Found: C, 47.18; H, 4.12; N, 11.59; Cu, 10.6. IR: ν_{CO} 2093 vs, 2045 w cm^{-1}.

$[Cu_2(HL\text{-}Et)(MeCN)_2][CF_3SO_3]_2$ (2). Dried acetonitrile (5 mL) was added to a mixture of HL-Et (0.182 g, 0.251 mmol) and $[Cu(MeCN)_4]CF_3SO_3$ (0.190 g, 0.503 mmol). The white solids dissolved rapidly to give a golden yellow solution that slowly turned orange-yellow. The solution was filtered and left to crystallize by vapor diffusion with diethyl ether over 4 days. Pale golden yellow crystals were manually separated from a green deposit. Anal. Calcd for $C_{49}H_{56}Cu_2N_{12}O_7F_6S_2$: C, 47.84; H, 4.59; N, 13.66; Cu, 10.33. Found: C, 47.99; H, 4.61; N, 13.74; Cu, 10.1. IR: ν_{CN} 2310 br, w cm^{-1}.

$[Cu_2(HCAB\text{-}Me)(MeCN)_2][CF_3SO_3]_2$ (3). Dried acetonitrile (5 mL) was added to a mixture of HCAB-Me (0.05 g, 0.067 mmol) and $[Cu(MeCN)_4]CF_3SO_3$ (0.051 g, 0.134 mmol). The solids dissolved to give a golden yellow solution from which colorless crystals were obtained in the same manner as for **2**. Anal. Calcd for $C_{51}H_{51}Cu_2N_{12}O_7F_6S_2$: C, 48.99; H, 4.19; N, 13.44; Cu, 10.16. Found: C, 49.23; H, 4.12; N, 13.35; Cu, 10.3. A reliable IR spectrum could not be obtained because of extreme air and KBr sensitivity.

$[Cu_2(HL\text{-}H)(MeCN)_2][ClO_4]_2 \cdot {}^1/_3Et_2O$ (4). Acetonitrile (5 mL) was added to a mixture of HL-H (0.154 g, 0.252 mmol) and $[Cu(MeCN)_4]ClO_4$ (0.165 g, 0.504 mmol). The colorless solids dissolved after ca. 15 min, and the solution was filtered and left to crystallize by vapor diffusion with diethyl ether overnight. Colorless crystals were collected by decanting. The presence of diethyl ether was detected by ^1H NMR spectroscopy in DMSO-d_6 (δ = 4.1 ppm, triplet, J = 7 Hz). Anal. Calcd for $C_{40.3}H_{43.3}N_{12}O_{9.3}Cu_2Cl_2$: C, 46.42; H, 4.18; N, 16.11; Cu, 12.18. Found: C, 46.24; H, 3.91; N, 16.83; Cu, 12.3. IR: ν_{CN} 2350 br, w cm^{-1}.

Caution! Perchlorate salts are potentially explosive. Although no detonation tendencies have been observed with **4**, caution is advised and handling of only small quantities is recommended.

$[Cu_2(HL\text{-}H)(CO)_2][BF_4]_2$ (5). Methanol (15 mL), HL-H (0.131 g, 0.215 mmol) with 5 mL of methanol, and $[Cu(MeCN)_4]BF_4$ (0.135 g, 0.430 mmol) were loaded into three separate Schlenk flasks. Upon removal from the glovebox each flask was flushed with carbon monoxide. The methanol was transferred onto the cuprous salt, which dissolved to give a colorless solution. This solution was transferred into the ligand solution, which gave a cloudy solution that was Schlenk filtered. When

(11) Alben, J. O.; Yen, L.; Farrier, N. J. *J. Am. Chem. Soc.* **1970**, *92*, 4475.
(12) Sorrell, T. N.; Jameson, D. L. *J. Am. Chem. Soc.* **1982**, *104*, 2053.
(13) Casella, L.; Gullotii, M.; Pallanza, G.; Rigoni, L. *J. Am. Chem. Soc.* **1988**, *110*, 4221.
(14) Dagdigian, J. V.; McKee, V.; Reed, C. A. *Inorg. Chem.* **1982**, *21*, 1332.
(15) Kau, L.-S.; Spira-Solomon, D. J.; Penner-Hahn, J. E.; Hodgson, K. O.; Solomon, E. I. *J. Am. Chem. Soc.* **1987**, *109*, 6433.
(16) Gagne, R. G.; Kreh, R. P.; Dodge, J. A.; Marsh, R. E.; McCool, M. *Inorg. Chem.* **1982**, *21*, 254.
(17) Karlin, K. D.; Haka, M. S.; Cruse, R. W.; Meyer, G. J.; Farooq, A.; Gultneh, Y.; Hayes, J. C.; Zubieta, J. *J. Am. Chem. Soc.* **1988**, *110*, 1196.
(18) Sorrell, T. N.; Borovik, A. S. *J. Am. Chem. Soc.* **1987**, *109*, 4255.
(19) Nelson, S. M.; Esho, F.; Lavery, A.; Drew, M. G. B. *J. Am. Chem. Soc.* **1983**, *105*, 5693.
(20) Pasquali, M.; Marini, G.; Floriani, C.; Gaetani-Manfredotti, A.; Guastini, C. *Inorg. Chem.* **1980**, *19*, 2525.
(21) Gelling, O. J.; van Bolhuis, F.; Meetsma, A.; Feringa, B. L. *J. Chem. Soc., Chem. Commun.* **1988**, 552.
(22) McKee, V.; Zvagulus, M.; Dagdigian, J. V.; Patch, M. G.; Reed, C. A. *J. Am. Chem. Soc.* **1984**, *106*, 4765.
(23) Chapman, D. R.; Reed, C. A. To be submitted for publication. See: Chapman, D. R.; Reed, C. A. *Tetrahedron Lett.* **1988**, *29*, 3033.
(24) Pate, J. E.; Ross, P. K.; Thamann, T. J.; Reed, C. A.; Karlin, K.; Sorrell, T. N.; Solomon, E. I. *J. Am. Chem. Soc.* **1989**, *111*, 5198.
(25) Mathur, P.; Crowther, M.; Dismukes, G. C. *J. Am. Chem. Soc.* **1987**, *109*, 5227.
(26) Chen, Q.; Lynch, J. B.; Gomez-Romero, P.; Ben-Hussein, A.; Jameson, G. B.; O'Conner, C. J.; Que, L. *Inorg. Chem.* **1988**, *27*, 2673.
(27) Kubas, G. J. *Inorg. Synth.* **1979**, *19*, 90.
(28) Hemmerich, P.; Sigwart, C. *Experientia* **1963**, *19*, 488.

Table I. Crystal Data for **1–4**

	1	2	3	4
empirical formula	$C_{47}H_{50}N_{10}O_9Cu_2F_6S_2$	$C_{49}H_{56}N_{12}O_7Cu_2F_6S_2$	$C_{51}H_{51}N_{12}N_7Cu_2F_6S_2$	$C_{39}H_{40}N_{12}O_9Cu_2Cl_2 \cdot {}^1/_3C_4H_{10}O$
fw	1204.2	1230.3	1250.3	1043.5
space group	$P\bar{1}$ (triclinic)	*Pbcn* (orthorhombic)	$P\bar{1}$ (triclinic)	*C*2/*c* (monoclinic)
a, Å	16.616 (8)	15.473 (5)	14.20 (1)	28.710 (9)
b, Å	11.884 (5)	16.369 (9)	13.39 (1)	7.600 (2)
c, Å	15.131 (4)	44.178 (17)	15.31 (1)	21.857 (9)
α, deg	106.69 (3)	90	104.52 (6)	90
β, deg	83.25 (3)	90	76.08 (7)	114.23 (3)
γ, deg	110.75 (4)	90	90.71 (8)	90
V, Å^3	2676 (2)	11 188 (9)	2731 (4)	4349 (3)
Z	2	8	2	4
radiation (λ, Å)	Mo Kα (0.710 69)	Mo Kα (0.710 69)	Mo Kα (0.710 69)	Mo Kα (0.710 69)
temp, °C	25	25	−100	−100
$(\sin\theta)/\lambda$ limit, Å^{-1}	0.5385	0.5385	0.5385	0.5385
total no. of rflns collected	7707	8565	7782	2825
no. of rflns used in refinement [$I > 3\sigma(I)$]	3680	2256	3554	1937
no. of params refined	699	768	750	304
R	0.0726	0.0773	0.0881	0.0537
R_w	0.0738	0.0781	0.0899	0.0688

Table II. Final Atomic Coordinates for $[Cu_2(HL\text{-}Et)(CO)_2][CF_3SO_3]_2$ (**1**)

atom	*x*	*y*	*z*	atom	*x*	*y*	*z*
Cu1	0.1122 (1)	0.1477 (1)	0.2866 (1)	C302	0.4327 (1)	0.7369 (1)	0.3255 (1)
C4	0.2188 (1)	0.1484 (1)	0.3036 (1)	N303	0.4797 (1)	0.6670 (1)	0.3196 (1)
O4	0.2840 (1)	0.1502 (1)	0.3140 (1)	C304	0.6393 (1)	0.7033 (1)	0.2947 (1)
C11	−0.0152 (1)	0.2652 (1)	0.4360 (1)	C305	0.7162 (1)	0.7953 (1)	0.2793 (1)
N101	−0.0949	0.0529 (1)	0.4630 (1)	C306	0.7157 (1)	0.9151 (1)	0.2796 (1)
C102	−0.0347 (1)	0.1250 (1)	0.4148 (1)	C307	0.6427 (1)	0.9479 (1)	0.2911 (1)
N103	0.0046 (1)	0.0615 (1)	0.3508 (1)	C308	0.5655 (1)	0.8541 (1)	0.3046 (1)
C104	−0.0144 (1)	−0.1684 (1)	0.2995 (1)	C309	0.5647 (1)	0.7384 (1)	0.3059 (1)
C105	−0.0638 (1)	−0.2817 (1)	0.3213 (1)	C310	0.4536 (1)	0.9602 (1)	0.3163 (1)
C106	−0.1287 (1)	−0.2866 (1)	0.3941 (1)	C311	0.4682 (1)	1.0582 (1)	0.4127 (1)
C107	−0.1434 (1)	−0.1788 (1)	0.4489 (1)	C44	0.3018 (1)	0.5333 (1)	0.1925 (1)
C108	−0.0935 (1)	−0.0680 (1)	0.4258 (1)	N401	0.3353 (1)	0.3803 (1)	0.0568 (1)
C109	−0.0326 (1)	−0.0619 (1)	0.3559 (1)	C402	0.3409 (1)	0.4356 (1)	0.1481 (1)
C110	−0.1463 (1)	0.0932 (1)	0.5443 (1)	N403	0.3866 (1)	0.3978 (1)	0.1908 (1)
C111	−0.2402 (1)	0.0571 (1)	0.5163 (1)	C404	0.4671 (1)	0.2420 (1)	0.1333 (1)
C22	−0.0260 (1)	0.2697 (1)	0.2779 (1)	C405	0.4856 (1)	0.1638 (1)	0.0503 (1)
N201	−0.0058 (1)	0.2301 (1)	0.1047 (1)	C406	0.4526 (1)	0.1523 (1)	−0.0360 (1)
C202	0.0179 (1)	0.2289 (1)	0.1870 (1)	C407	0.3998 (1)	0.2189 (1)	−0.0470 (1)
N203	0.0805 (1)	0.1817 (1)	0.1783 (1)	C408	0.3835 (1)	0.2990 (1)	0.0391 (1)
C204	0.1587 (1)	0.0918 (1)	0.0365 (1)	C409	0.4162 (1)	0.3103 (1)	0.1253 (1)
C205	0.1600 (1)	0.0691 (1)	−0.0586 (1)	C410	0.2938 (1)	0.4072 (1)	−0.0122 (1)
C206	0.1037 (1)	0.1008 (1)	−0.1045 (1)	C411	0.3605 (1)	0.5027 (1)	−0.0570 (1)
C207	0.0437 (1)	0.1559 (1)	−0.0585 (1)	S1	0.8059 (1)	0.2125 (1)	0.8405 (1)
C208	0.0455 (1)	0.1800 (1)	0.0382 (1)	O1	0.8601 (1)	0.1583 (1)	0.8600 (1)
C209	0.0992 (1)	0.1494 (1)	0.0841 (1)	O2	0.8329 (1)	0.3458 (1)	0.8769 (1)
C210	−0.0748 (1)	0.2734 (1)	0.0896 (1)	O3	0.7765 (1)	0.1798 (1)	0.7530 (1)
C211	−0.0378 (1)	0.4130 (1)	0.0904 (1)	C6	0.7161 (1)	0.1694 (1)	0.9117 (1)
N1	0.0336 (1)	0.3076 (1)	0.3564 (1)	F1	0.6799 (1)	0.0489 (1)	0.8861 (1)
C1	0.0710 (1)	0.4473 (1)	0.3908 (1)	F2	0.7284 (1)	0.1956 (1)	0.9945 (1)
CAB	0.1445 (1)	0.5125 (1)	0.3299 (1)	F3	0.6538 (1)	0.2050 (1)	0.8973 (1)
OA	0.1464 (1)	0.6354 (1)	0.3537 (1)	S2	0.7520 (1)	0.3263 (1)	0.3734 (1)
OB	0.1163 (1)	0.4978 (1)	0.2423 (1)	O6	0.6882 (1)	0.2684 (1)	0.4287 (1)
C3	0.2210 (1)	0.4793 (1)	0.3364 (1)	O7	0.7774 (1)	0.2177 (1)	0.3104 (1)
N2	0.3038 (1)	0.5591 (1)	0.2953 (1)	O8	0.8241 (1)	0.4200 (1)	0.3956 (1)
Cu2	0.4094 (1)	0.4902 (1)	0.3236 (1)	C7	0.7018 (1)	0.3355 (1)	0.2791 (1)
C5	0.4073 (1)	0.4271 (1)	0.4169 (1)	F4	0.6364 (1)	0.2584 (1)	0.2575 (1)
O5	0.4056 (1)	0.3855 (1)	0.4746 (1)	F5	0.7509 (1)	0.4060 (1)	0.2394 (1)
C33	0.3355 (1)	0.6933 (1)	0.3407 (1)	F6	0.6657 (1)	0.4331 (1)	0.3243 (1)
N301	0.4810 (1)	0.8526 (1)	0.3179 (1)				

this solution stood under CO for 2 weeks, colorless needles were formed. These were separated from the pale blue mother liquor by decanting. Anal. Calcd for $C_{37}H_{34}N_{10}O_3B_2F_8Cu_2$: C, 45.94; H, 3.54; N, 14.48. Found: C, 46.01; H, 4.33; N, 13.90. IR: ν_{CO} 2080 vs cm^{-1}.

X-ray Crystallography. Structures **1–3** were determined on a Nicolet/Syntex $P2_1$ diffractometer at the University of Southern California; structure **4** was ascertained on Nicolet R3m instrumentation at the University of Canterbury. Key facets of the four structure determinations are given in Table I. Additional information is given in the narratives below. In all cases the crystals were grown according to the synthetic procedures outlined above.

$[Cu_2(HL\text{-}Et)(CO)_2][CF_3SO_3]_2$ (1). A colorless crystal of approximate dimensions 0.6 × 0.3 × 0.3 mm was selected under argon and sealed in a capillary in air. Unit cell parameters were determined from 15 reflections and data collected by using ω scans with $4° < 2\theta < 45°$ and variable scan rates from 2.0 to 15.0° min^{-1}. The crystal stability was monitored by recording three standard reflections every 50 reflections; no significant variation was observed. Intensities were corrected for Lorentz polarization effects and absorption. The positions of the copper atoms were obtained by Patterson methods with use of the computer package SHELX 84.[29]

The remaining non-hydrogen atoms were located from difference Fourier maps by using SHELX 76.[29] The two crystallographically independent triflate anions were found to be ordered. The alcohol oxygen

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Table III. Final Atomic Coordinates for $[Cu_2(HL\text{-}Et)(MeCN)_2][CF_3SO_2]_2$ (2)

atom	x	y	z	atom	x	y	z
Cu1	0.4735 (1)	0.2863 (1)	0.5693 (1)	C304	0.3712 (1)	−0.1424 (1)	0.7275 (1)
N3	0.5229 (1)	0.2096 (1)	0.5421 (1)	C305	0.3572 (1)	−0.2266 (1)	0.7362 (1)
C4	0.5546 (1)	0.1657 (1)	0.5257 (1)	C306	0.4086 (1)	−0.2862 (1)	0.7268 (1)
C5	0.5993 (2)	0.1152 (1)	0.5021 (1)	C307	0.4817 (1)	−0.2830 (1)	0.7080 (1)
C11	0.6241 (1)	0.3807 (1)	0.5994 (1)	C308	0.4965 (1)	−0.2007 (1)	0.6989 (1)
N101	0.5816 (1)	0.5154 (1)	0.5740 (1)	C309	0.4453 (1)	−0.1371 (1)	0.7069 (1)
C102	0.5690 (1)	0.4341 (1)	0.5777 (1)	C310	0.6532 (2)	−0.2205 (1)	0.6714 (1)
N103	0.5082 (1)	0.4041 (1)	0.5612 (1)	C311	0.6211 (2)	−0.2543 (2)	0.6436 (1)
C104	0.4045 (1)	0.4711 (1)	0.5257 (1)	C44	0.4902 (1)	0.0011 (1)	0.6215 (1)
C105	0.3842 (1)	0.5543 (2)	0.5142 (1)	N401	0.3375 (1)	0.0272 (1)	0.6265 (1)
C106	0.4315 (2)	0.6211 (5)	0.5214 (1)	C402	0.3991 (1)	0.0272 (1)	0.6265 (1)
C107	0.4989 (1)	0.6223 (1)	0.5419 (1)	N403	0.3640 (1)	0.0576 (1)	0.6518 (1)
C108	0.5202 (1)	0.5433 (1)	0.5532 (1)	C404	0.2106 (1)	0.0932 (1)	0.6655 (1)
C109	0.4765 (1)	0.4702 (1)	0.5461 (1)	C405	0.1275 (1)	0.0943 (1)	0.6532 (1)
C110	0.6591 (2)	0.5680 (1)	0.5852 (1)	C406	0.1097 (1)	0.0661 (1)	0.6232 (1)
C111	0.6311 (3)	0.6118 (3)	0.6031 (1)	C407	0.1735 (1)	0.0384 (1)	0.6044 (1)
C112	0.7282 (2)	0.5821 (2)	0.5660 (1)	C408	0.2574 (1)	0.0382 (1)	0.6166 (1)
N1	0.5608 (1)	0.3207 (1)	0.6121 (1)	C409	0.2754 (1)	0.0670 (1)	0.6454 (1)
C22	0.5020 (1)	0.3599 (1)	0.6338 (1)	C410	0.3480 (1)	−0.0168 (1)	0.5722 (1)
N201	0.3419 (1)	0.3467 (1)	0.6456 (1)	C411	0.3514 (1)	0.0565 (1)	0.5506 (1)
C202	0.4116 (1)	0.3336 (1)	0.6267 (1)	S11	0.6546 (1)	0.4873 (1)	0.1853 (1)
N203	0.3860 (1)	0.3018 (1)	0.6009 (1)	O11	0.6858 (1)	0.4473 (1)	0.6679 (1)
C204	0.2366 (1)	0.2612 (1)	0.5807 (1)	O12	0.5691 (1)	0.5325 (1)	0.6770 (1)
C205	0.1491 (1)	0.2644 (1)	0.5894 (1)	O13	0.7093 (1)	0.5742 (1)	0.6935 (1)
C206	0.1258 (1)	0.2909 (1)	0.6178 (1)	C11	0.6715 (2)	0.4621 (2)	0.7181 (1)
C207	0.1785 (1)	0.3231 (1)	0.6409 (1)	F111	0.6477 (3)	0.4744 (2)	0.7453 (1)
C208	0.2675 (1)	0.3195 (1)	0.6303 (1)	F112	0.6191 (3)	0.4085 (3)	0.7189 (2)
C209	0.2962 (1)	0.2925 (1)	0.6026 (1)	F113	0.5799 (3)	0.4745 (3)	0.7225 (1)
C210	0.3466 (1)	0.3823 (1)	0.6777 (1)	F11	0.5663 (2)	0.3986 (2)	0.7149 (1)
C211	0.3591 (1)	0.3085 (1)	0.7008 (1)	F12	0.5939 (3)	0.5246 (2)	0.7368 (1)
C1	0.6104 (1)	0.2515 (1)	0.6252 (1)	F13	0.7297 (2)	0.4285 (2)	0.7252 (1)
C2	0.5483 (1)	0.1776 (1)	0.6312 (1)	S22	0.6096 (1)	0.1245 (1)	0.0606 (1)
O1	0.5014 (1)	0.1962 (1)	0.6591 (1)	O21	0.8395 (1)	0.4055 (1)	0.5839 (1)
C3	0.6017 (1)	0.0995 (1)	0.6365 (1)	O22	0.9234 (2)	0.4405 (1)	0.5432 (1)
N2	0.5462 (1)	0.0316 (1)	0.6464 (1)	O23	0.9564 (1)	0.3230 (1)	0.5651 (1)
Cu2	0.4243 (1)	0.0437 (1)	0.6907 (1)	C21	0.8244 (2)	0.3187 (2)	0.5337 (1)
N4	0.4043 (1)	0.1056 (1)	0.7256 (1)	F21	0.3666 (1)	0.2017 (2)	0.4883 (2)
C6	0.3875 (1)	0.1372 (1)	0.7481 (1)	F22	0.7387 (3)	0.1125 (3)	0.0290 (1)
C7	0.3666 (1)	0.1771 (1)	0.7781 (1)	F23	0.7198 (2)	0.2395 (2)	0.0494 (1)
C33	0.6015 (1)	−0.0342 (1)	0.6592 (1)	F221	0.8169 (3)	0.3629 (3)	0.5113 (1)
N301	0.5617 (1)	−0.1723 (1)	0.6796 (1)	F222	0.7476 (2)	0.3339 (2)	0.5345 (1)
C302	0.5455 (1)	−0.0916 (1)	0.6776 (1)	F223	0.8385 (3)	0.2566 (3)	0.5387 (2)
N303	0.4776 (1)	−0.0663 (1)	0.6933 (1)				

of HL-Et was found to be disordered and was modeled with 50% occupancy at positions OA and OB. Blocked least-squares refinement treating all non-hydrogen atoms anisotropically resulted in a conventional $R = 0.073$. Final atomic coordinates are given in Table II. Anisotropic thermal parameters are listed in Table S1 of the supplementary material together with complete listings of bond distances and angles (Tables s2 and s3, respectively).

$[Cu_2(HL\text{-}Et)(MeCN)_2][CF_3SO_3]_2$ (2). Inside a drybox a colorless crystal of approximate dimensions 0.7 × 0.5 × 0.3 mm was removed from the mother liquor with a spatula coated with Paratone N oil[30] and placed in a petri dish containing the oil. With use of a glass fiber tipped with silicone grease, the crystal was transferred to a capillary, which was plugged with grease, removed from the glovebox, and flame sealed. Preliminary centering revealed that the crystal was not immobilized in the capillary. However, when the goniometer head was repositioned by 180° with an inverted capillary tube, the crystal fell to the end of the capillary and became stationary after 2 days. Subsequent alignment was done with this χ inversion technique without discernable movement of the crystal. Data collection, solution, and refinement followed the same procedures as above. The methyl group of the ethyl substituent on N101 was found to be disordered and was refined with two positions of half occupancy (C111 and C112). Similarly, the CF_3 groups on the crystallographically independent triflate anions were refined in two different positions of 50% occupancy. Final atomic coordinates are given in Table III. Tables S4–S6 in the supplementary material give anisotropic temperature factors, bond distances, and angles, respectively.

$[Cu_2(HCAB\text{-}Me)(CH_3CH)_2][CF_3SO_3]_2$ (3). Inside a drybox, a pale golden crystal of approximate dimensions 1.0 × 0.7 × 0.7 mm was transferred from the mother liquor to a petri dish containing Paratone N oil with use of a Paratone N oil coated spatula. This was placed in a small desiccator and transported to the diffractometer, where the crystal was quickly mounted in air onto a silicone grease tipped glass fiber already mounted on a goniometer head. This was placed in the cold stream of the LT-1 low-temperature device and aligned manually with partial disassembly of the cold-N_2 delivery system. Data were collected as above. Although no variation of standard reflections was observed with time, the crystal had turned pale pink by the end of data collection. Solution and refinement proceeded as above. One of the two crystallographically independent triflate anions was found to have a disordered CF_3 group, which was modeled with four F sites of 75% occupancy each. Final atomic coordinates are given in Table IV. Tables S7, S8, and S9 in the supplementary material give listings of the anisotropic temperature factors, bond lengths, and bond angles, respectively.

$[Cu_2(HL\text{-}H)(MeCN)_2][ClO_4]_2 \cdot {}^1/_3Et_2O$ (4). A crystal of approximate dimensions 0.4 × 0.3 × 0.2 mm was removed from the mother liquor and coated with silicone grease inside a glovebox and mounted on a glass fiber. This was carried to the diffractometer under an inert atmosphere and rapidly mounted in the cold stream. Cell parameters were determined from 25 accurately centered reflections. Due to the presence of a 28-Å axis data were collected by using 2.0° ω scans with variable scan rates (4.88–29.3° min^{-1}). Crystal stability was confirmed by the lack of significant variation of 3 standard reflections measured every 100 reflections. Intensities were corrected for Lorentz polarization effects, but an absorption correction made no improvement and was abandoned. The copper and chlorine atoms were located from a Patterson calculation, and the other non-hydrogen atoms were found from difference Fourier maps. The structure was refined by blocked-cascade least squares to give $R = 0.089$. Anisotropic refinement of all non-hydrogen atoms (except those of a one-third-occupancy ether molecule) was carried out, and hydrogen atoms were inserted at calculated positions for appropriate nondisordered, full-occupancy atoms. The C–H or N–H distances were fixed at 0.96 Å, and the hydrogen thermal parameters were fixed at 1.2 times the

(30) Obtained from Exxon Chemicals, Paramins Technology Services Dept., P.O. Box 536, Linden, NJ 07036.

Table IV. Final Atomic Coordinates for $[Cu_2(HCAB\text{-}Me)(MeCN)_2][CF_3SO_2]_2$ (3)

atom	x	y	z	atom	x	y	z
S1	0.0221 (1)	0.4800 (1)	0.7545 (1)	C7	1.2507 (1)	0.2173 (1)	0.4295 (1)
O2	0.0859 (1)	0.4171 (1)	0.7775 (1)	C8	1.1941 (1)	0.1502 (1)	0.4887 (1)
O3	0.0663 (1)	0.5623 (1)	0.7242 (1)	C9	1.1698 (1)	0.0514 (1)	0.4496 (1)
O4	−0.0470(1)	0.4195 (1)	0.7086 (1)	C10	1.1269 (1)	−0.0111 (1)	0.5072 (1)
C1	−0.0447 (1)	0.5342 (1)	0.8680 (1)	C12	1.1091 (1)	0.0263 (1)	0.6023 (1)
F1	−0.0969 (1)	0.4757 (1)	0.9075 (1)	C13	1.1294 (1)	0.1260 (1)	0.6407 (1)
F2	0.0016 (1)	0.5904 (1)	0.9227 (1)	C14	1.1723 (1)	0.1910 (1)	0.5870 (1)
F3	−0.1086 (1)	0.6080 (1)	0.8655 (1)	O1	1.1954 (1)	0.2885 (1)	0.6191 (1)
S2	0.4422 (1)	0.3154 (1)	0.0791 (1)	C15	1.1015 (1)	−0.1233 (1)	0.4643 (1)
O5	0.5334 (1)	0.3098 (1)	0.0781 (1)	C16	1.1172 (1)	0.1648 (1)	0.7503 (1)
O6	0.4846 (1)	0.4063 (1)	0.0071 (1)	N2	1.0185 (1)	0.1384 (1)	0.7974 (1)
O7	0.3807 (1)	0.2566 (1)	0.0189 (1)	Cu2	0.9475 (1)	−0.0509 (1)	0.7822 (1)
C2	0.3618 (1)	0.3878 (1)	0.1302 (1)	C33	0.9408 (1)	0.2014 (1)	0.7894 (1)
F4	0.3330 (1)	0.4681 (1)	0.1131 (1)	N301	0.7592 (1)	0.1961 (1)	0.8259 (1)
F5	0.3459 (1)	0.3418 (2)	0.2021 (1)	C302	0.8461 (1)	0.1485 (1)	0.8042 (1)
F6	0.2959 (2)	0.3567 (2)	0.1173 (2)	N303	0.8384 (1)	0.0485 (1)	0.8026 (1)
F7	0.4560 (1)	0.4881 (1)	0.1586 (1)	C304	0.6914 (1)	−0.0643 (1)	0.8302 (1)
Cu1	1.4036 (1)	0.2718 (1)	0.6052 (1)	C305	0.5872 (1)	−0.0465 (1)	0.8575 (1)
C11	1.4006 (1)	0.2959 (1)	0.3910 (1)	C306	0.5424 (1)	0.0502 (1)	0.8770 (1)
N101	1.5644 (1)	0.3786 (1)	0.3884 (1)	C307	0.5856 (1)	0.1423 (1)	0.8663 (1)
C102	1.4860 (1)	0.3373 (1)	0.4330 (1)	C308	0.6887 (1)	0.1226 (1)	0.8382 (1)
N103	1.4945 (1)	0.3371 (1)	0.5179 (1)	C309	0.7381 (1)	0.0293 (1)	0.8206 (1)
C104	1.6289 (1)	0.3979 (1)	0.6047 (1)	C310	0.7386 (1)	0.3037 (1)	0.8356 (1)
C105	1.7234 (1)	0.4417 (1)	0.5894 (1)	C44	1.0185 (1)	0.1511 (1)	0.8969 (1)
C106	1.7622 (1)	0.4646 (1)	0.4996 (1)	N401	1.1399 (1)	0.0527 (1)	0.9479 (1)
C107	1.7161 (1)	0.4503 (1)	0.4268 (1)	C402	1.0659 (1)	0.0565 (1)	0.9038 (1)
C108	1.6284 (1)	0.4067 (1)	0.4453 (1)	N403	1.0422 (1)	−0.0371 (1)	0.8648 (1)
C109	1.5836 (1)	0.3828 (1)	0.5291 (1)	C404	1.1091 (1)	−0.2108 (1)	0.8508 (1)
C110	1.5781 (1)	0.3944 (1)	0.2920 (1)	C405	1.1801 (1)	−0.2594 (1)	0.8778 (1)
C22	1.4057 (1)	0.1219 (1)	0.4049 (1)	C406	1.2436 (1)	−0.2009 (1)	0.9302 (1)
N201	1.3740 (1)	−0.0302 (1)	0.4733 (1)	C407	1.2372 (1)	−0.0959 (1)	0.9584 (1)
C202	1.3923 (1)	0.0697 (1)	0.4833 (1)	C408	1.1641 (1)	−0.0484 (1)	0.9326 (1)
N203	1.3951 (1)	0.1199 (1)	0.5689 (1)	C409	1.1035 (1)	−0.1076 (1)	0.8815 (1)
C204	1.3671 (1)	0.0605 (1)	0.7167 (1)	C410	1.1845 (1)	0.1444 (1)	0.9987 (1)
C205	1.3419 (1)	−0.0254 (1)	0.7498 (1)	N3	1.3552 (1)	0.3456 (1)	0.7357 (1)
C206	1.3248 (1)	−0.1220 (1)	0.6900 (1)	C3	1.3253 (1)	0.3862 (1)	0.8074 (1)
C207	1.3346 (1)	−0.1321 (1)	0.5955 (1)	C4	1.2780 (1)	0.4435 (1)	0.9062 (1)
C208	1.3600 (1)	−0.0471 (1)	0.5619 (1)	N4	0.9584 (1)	−0.1805 (1)	0.6886 (1)
C209	1.3740 (1)	0.0462 (1)	0.6184 (1)	C5	0.9674 (1)	−0.2541 (1)	0.6338 (1)
C210	1.3706 (1)	−0.1123 (1)	0.3888 (1)	C6	0.9845 (1)	−0.3535 (1)	0.5625 (1)
N1	1.3534 (1)	0.2219 (1)	0.4372 (1)				

equivalent isotropic U values of their carrier atoms. The refinement converged with a conventional $R = 0.0537$ and weighted $R_G = 0.0688$, where the function minimized was $\sum w(|F_o| - |F_c|)^2$ and $w = [\sigma^2(F_o) + 0.0013(F_o)^2]^{-1}$. A final difference map showed no features greater than +0.5 e Å^{-3} and showed a maximum least-squares shift to error ratio of 0.193 (mean 0.018). The carbon atom C1 sits on a crystallographic 2-fold axis, and the attached alcohol oxygen is disordered, having 50% occupancy in each of the two sites O1 and O1′. The oxygen atom of a solvate ether molecule (O40) also sits on the 2-fold axis. This molecule has been refined isotropically with one-third occupancy. Final atomic coordinates are listed in Table V. Tables S10–S12 in the supplementary material give anisotropic temperature factors, bond lengths, and bond angles, respectively.

Results and Discussion

Synthesis. The synthesis of isolable, pure copper(I) complexes has rarely proved to be straightforward with the present tetrabenzimidazole-type ligands. The synthesis of the carbonyl complex **1**, for example, appears to involve some degree of disproportionation/conproportionation. A methanolic solution of HL-Et and a copper(I) tetrakis(acetonitrile) salt produces a brick red precipitate (presumably copper metal) in a pale blue solution (presumably copper(II)). Carbon monoxide slowly decolorizes this suspension upon sitting overnight. A similar observation has been made in early copper(I) carbonyl work.[31] One aspect worth noting with regard to the synthesis of the acetonitrile complexes is the need for carefully dried solvent for **2** and **3** but the need for trace water (0.005%) for **4**. In wet acetonitrile **2** and **3** decompose to give a green product (presumably copper(II)) upon ether diffusion. In dry acetonitrile **4** has such low solubility it would be impractical to grow X-ray-quality crystals. With the exception of the carbonyl **1**, air and moisture sensitivity and/or solvent (or CO) loss make all the compounds difficult to handle even in the solid state. Rapid removal of crystals from the mother liquor, application of a grease or oil coating, and data collection at low temperature were required for crystallography in most cases. Despite considerable effort we have been unable to find preparative conditions for the isolation of copper(I) complexes with the alcohol-deprotonated ligands L-H$^-$, L-Et$^-$, and CAB-Me$^-$. In earlier work with copper(II) we had observed facile deprotonation and the formation of alkoxide-bridged dimers.[22,32] Problems of disproportionation are evident from the common appearance of blue or green supernatants. The solubility of ionic materials is a related problem since the higher solvent polarity required for dissolution of salts appears to accelerate redox decomposition. Nevertheless, with the inclusion of a π-acceptor ligand such as CO or MeCN in the coordination sphere we are able to extend considerably the known range of binuclear copper(I) complexes with benzimidazole chelates. The characterization of these complexes has been largely limited to the solid state by the solution instability alluded to above. ^{1}H NMR data showed broad peaks (possibly due to traces of Cu(II)) and were not particularly informative.

The vibrational data on the acetonitrile complexes **2** and **4** show ν_{CN} bands 50–100 cm^{-1} above those of free acetonitrile, as observed in other copper(I) acetonitrile complexes.[33] The major carbonyl stretching frequencies in **1** and **5** are found at 2093 and 2080 cm^{-1}, respectively. These values are near the middle of the range for

(31) Pasquali, M.; Floriani, C.; Gaetani-Manfredotti, A. *Inorg. Chem.* **1980**, *19*, 1191.

(32) McKee, V.; Zvagulis, M.; Reed, C. A. *Inorg. Chem.* **1985**, *24*, 2914.

(33) Rhodes, L. F.; Huffman, J. C.; Caulton, K. G. *J. Am. Chem. Soc.* **1985**, *107*, 1759.

Table V. Final Atomic Coordinates for $[Cu_2(HL\text{-}H)(MeCN)_2][ClO_4]_2 \cdot {}^1/_3Et_2O$ (**4**)

atom	*x*	*y*	*z*
Cu	0.1573 (1)	0.6352 (1)	0.5488 (1)
O1	0.0297 (4)	0.6291 (13)	0.2191 (4)
C1	0	0.6192 (14)	0.2500
C2	0.0383 (2)	0.7327 (9)	0.3040 (3)
N1	0.0817 (2)	0.6322 (7)	0.3507 (2)
C10	0.1238 (2)	0.7517 (8)	0.3890 (3)
C11	0.1721 (2)	0.6561 (9)	0.4236 (3)
N11	0.1906 (2)	0.6026 (7)	0.4873 (2)
C12	0.2373 (2)	0.5237 (8)	0.4993 (3)
C13	0.2723 (3)	0.4443 (9)	0.5574 (3)
C14	0.3154 (2)	0.3721 (9)	0.5550 (4)
C15	0.3239 (3)	0.3796 (10)	0.4963 (4)
C16	0.2893 (3)	0.4624 (9)	0.4378 (4)
C17	0.2462 (2)	0.5288 (9)	0.4414 (3)
N12	0.2041 (2)	0.6165 (7)	0.3951 (3)
C20	0.0688 (2)	0.5129 (9)	0.3949 (3)
C21	0.0513 (2)	0.5997 (9)	0.4428 (3)
N21	0.0821 (2)	0.6507 (7)	0.5046 (2)
C22	0.0501 (2)	0.7258 (9)	0.5316 (3)
C23	0.0615 (3)	0.8001 (9)	0.5934 (3)
C24	0.0215 (3)	0.8700 (10)	0.6057 (4)
C25	−0.0280 (3)	0.8652 (9)	0.5572 (4)
C26	−0.0402 (3)	0.7917 (9)	0.4950 (4)
C27	0.0002 (3)	0.7224 (9)	0.4835 (3)
N22	0.0025 (2)	0.6422 (7)	0.4283 (3)
N30	0.1893 (2)	0.6670 (8)	0.6436 (3)
C31	0.2011 (3)	0.7043 (11)	0.6987 (4)
C32	0.2140 (3)	0.7518 (13)	0.7677 (3)
Cl	0.3584 (1)	0.7372 (3)	0.7914 (1)
O11	0.3166 (2)	0.8275 (9)	0.7423 (3)
O12	0.3761 (3)	0.6037 (9)	0.7615 (4)
O13	0.3453 (3)	0.6667 (13)	0.8411 (4)
O14	0.3980 (3)	0.8641 (11)	0.8194 (4)
O40	0	0.1678 (34)	0.2500
C41	0.0491 (16)	0.2094 (61)	0.2687 (21)
C42	0.1032 (8)	0.2959 (31)	0.2802 (11)

copper(I) complexes[13] suggestive of moderate binding strength. This is consistent with the observation that dissolution of **1** in acetonitrile causes effervescence, presumably because of CO replacement by this solvent.

The Carbonyl Structure 1. The X-ray crystal structure of $[Cu_2(HL\text{-}Et)(CO)_2][CF_3SO_3]_2$ consists of discrete cations and anions with two molecules in the unit cell. A perspective view of the cation is displayed in Figure 1 along with the atom-numbering scheme. The two copper centers are 5.35 Å apart and are symmetry independent. The potentially ligating 2-hydroxy group of the propylenediamine backbone of HL-Et is nonligating and shows 2-fold disorder.

The inner coordination sphere of each copper center is shown in Figure 2. Each copper atom is nominally four-coordinate with ligation by two benzimidazoles, the tertiary amine, and CO. A casual view of the coordination geometry might suggest a pseudotetrahedron, but a more appropriate description is that of a distorted trigonal pyramid. The CO ligand and the two benzimidazoles form the basal trigonal plane. The tertiary amine forms

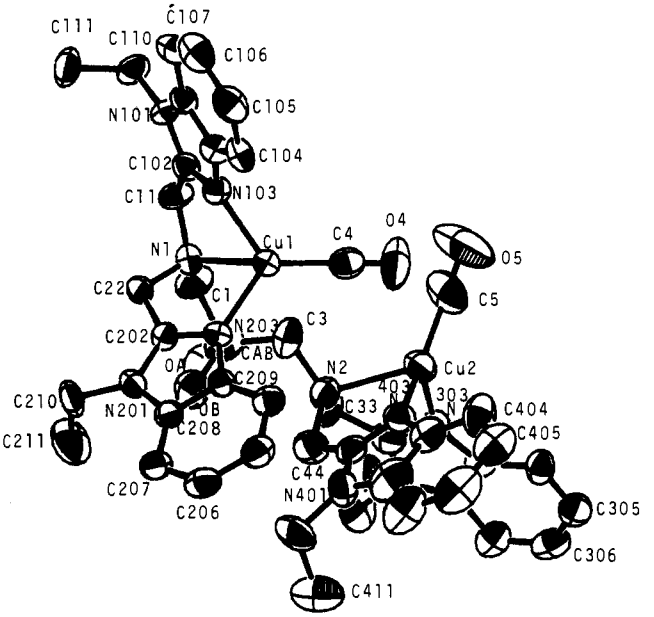

Figure 1. Perspective drawing of the dication of **1**, $[Cu_2(HL\text{-}Et)(CO)_2]^{2+}$, with thermal ellipsoids contoured at the 50% probability level. For clarity some atoms are unnumbered. Their labels are readily deduced by the sequential numbering patterns of successive rings, which follow systematic nomenclature.

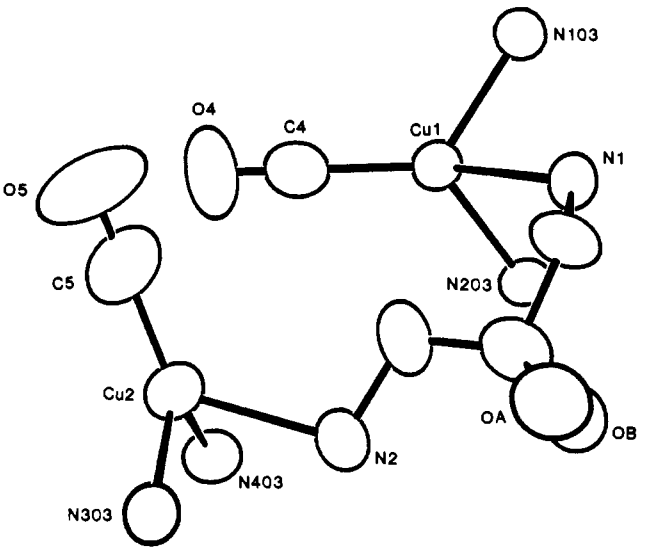

Figure 2. View of the distorted-trigonal-pyramidal inner coordination spheres in $[Cu_2(HL\text{-}Et)(CO)_2]^{2+}$ (**1**). The basal trigonal array is most easily seen for Cu2 with N2 at the elongated, off-axis apex.

the elongated, off-normal apex. This is most readily seen for Cu2 on the left-hand side of Figure 2. Table VI lists the coordination bond lengths and angles for each copper atom in **1** (as well as those for **2**–**4** discussed below). The interligand bond angles in the basal

Table VI. Bond Distances (Å) and Angles (deg) Pertinent to the Copper Coordination Geometry for Complexes **1**–**4**

	1		**2**		**3**		**4**
	Cu1	Cu2	Cu1	Cu2	Cu1	Cu2	Cu
$Cu\text{-}N_{amine}$	2.59 (1)	2.31 (1)	2.39 (1)	2.72 (1)	2.73 (1)	2.69 (1)	3.968
$Cu\text{-}N_{aromatic}$	2.01 (1)	2.03 (1)	2.03 (1)	1.98 (1)	1.98 (1)	1.99 (1)	1.959 (6)
	1.96 (1)	2.00 (1)	1.96 (1)	1.97 (1)	1.99 (1)	2.01 (1)	1.975 (5)
Cu–L[a]	1.82 (2)	1.77 (2)	1.90 (2)	1.87 (2)	1.96 (1)	1.94 (1)	1.907 (5)
$N_{amine}\text{-}Cu\text{-}N_{aromatic}$	72.6 (4)	79.0 (4)	78 (1)	72 (1)	71.0 (4)	70.9 (4)	
	76.1 (4)	79.7 (4)	77 (1)	73 (1)	73.3 (4)	73.6 (4)	
$N_{amine}\text{-}Cu\text{-}L$[a]	132.4 (4)	124.7 (5)	115 (1)	138 (1)	142.1 (4)	138.3 (4)	
$N_{aromatic}\text{-}Cu\text{-}N_{aromatic}$	109.3 (4)	103.8 (4)	101 (1)	111 (1)	117.8 (4)	124.3 (4)	114.6 (2)
$N_{aromatic}\text{-}Cu\text{-}L$	124.2 (6)	124.6 (4)	114 (1)	121 (1)	120.6 (5)	120.6 (5)	127.5 (2)
	132.9 (5)	127.5 (5)	145 (1)	125 (1)	119.1 (5)	114.6 (5)	117.8 (3)

[a] L = CO or MeCN.

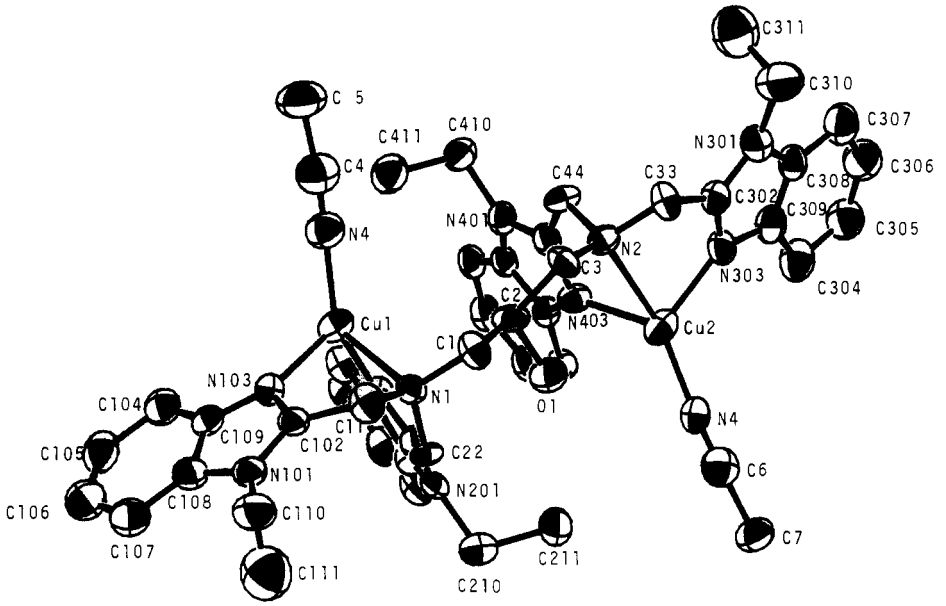

Figure 3. Perspective drawing of the dication of **2**, $[Cu_2(HL\text{-}Et)(MeCN)_2]^{2+}$, with thermal ellipsoids contoured at the 50% probability level. See the caption to Figure 1 regarding the numbering pattern.

plane are all within 16° of the trigonal expectation of 120°. The three angles sum to 357° for Cu1 and 356° for Cu2, consistent with the small displacements of the Cu atoms from the basal trigonal planes (0.18 and 0.22 Å, respectively, for Cu1 and Cu2).

The unusual feature of each copper center is the long, off-normal bond to the apical amine nitrogen atom. The N–Cu–N angles of the amine to the basal benzimidazoles are very acute and lie in the range 72–80°. This appears to be a consequence of the limited bite of the five-membered chelate rings. The corresponding angles in copper(II) complexes of L-Et such as $[Cu_2(OAc)(L\text{-}Et)]^{2+}$ and $[Cu_2(N_3)(L\text{-}Et)]^{2+}$ are in the range 80.5–83.4°.[22]

The Cu–N distances to the apical amine nitrogen atom are long: 2.59 Å for Cu1 and 2.31 Å for Cu2. This again must be largely a consequence of the limited bite of the five-membered chelate but also reflects the compromise between trigonal-planar three-coordination and tetrahedral four-coordination. The Cu–N–C angles around the tertiary amine nitrogen atom (103.6, 97.2, and 129° at Cu1 and 103.5, 105.8, and 103.9° at Cu2) cluster around the tetrahedral angle of 109°, suggesting that the lone pair is appropriately oriented for effective donation.

The partial four-coordination seen in the present copper(I) carbonyl complex has no precedent in binuclear copper carbonyls, but two precedents can be found in mononuclear species. In the ethylenediamine carbonyl complex $[Cu(en)(CO)]BPh_4$ there is an apical interaction of the copper atom with one arene ring of the tetraphenylborate anion.[31] Similarly, in the chelating bis(pyridine) carbonyl complex $[Cu(NH(py)_2)(CO)]ClO_4$[34] the perchlorate ion is apically coordinated at 2.43 Å in a trigonal-pyramidal stereochemistry. The copper atom is respectively 0.26 and 0.16 Å out of the plane of the basal donor atoms in these two structures. In both of these structures there is a charge attraction of the cationic copper complex for its counterion that is apparently thwarted in **1**. Nevertheless, the attainment of some degree of four-coordination occurs via the tertiary amine, which only serves to underscore the observation of a tendency toward four-coordination made earlier by Pasquali et al.[31] Why some degree of tetracoordination is apparently necessary in this type of copper carbonyl complex, albeit weak and distorted, remains poorly understood. To date there is but a single definitively characterized three-coordinate copper(I) carbonyl complex, the recently reported binuclear tropocoronand $Cu_2(CO)_2(TC\text{-}5,5)$.[35] As expected, the geometry is trigonal. The key factor for achieving three-coordination in this complex may be the internal charge compensation by the ligand, which is uninegative on a per copper basis. Another difference is the aliphatic nitrogen donors of the tropocoronand versus the aromatic donors of the benzimidazoles in the present work. The basic trigonal array of the carbonyl and its two major ligands, seen now in four separate compounds, contrasts with the more predictable features of tetrahedrally coordinated four-coordinate carbonyls such as $[Cu_2(TPEN)(CO)_2]^{2+}$.[16] Curiously, this particular example actually has five-membered chelating rings and yet can attain a reasonable approximation of tetrahedrality. Evidently the constraints of our bulky benzimidazole chelating ligands are a little more sterically demanding than those of related chelating pyridine ligands. As will be seen below, the use of HL-H instead of HL-Et gives rise to three-coordination rather than four-coordination when the added ligand is acetonitrile rather than CO. This observation is a tantalizing one inasmuch as it suggests a three-coordinate carbonyl might exist in $[Cu_2(HL\text{-}H)(CO)_2]^{2+}$. We have prepared this species and characterized it as its tetrafluoroborate salt **5** but to date have been unable to obtain crystals suitable for X-ray crystallography. The carbonyl stretching frequency of **1** is about 13 cm^{-1} greater than that of **5**, which is perhaps consistent with a change in coordination number, but without crystallographic characterization there can be no proof of an exception to the generalization that cationic copper(I) carbonyls are always four-coordinate to some extent.

The Four-Coordinate Acetonitrile Complex 2. The X-ray crystal structure of $[Cu_2(HL\text{-}Et)(CH_3CN)_2][CF_3SO_3]_2$ consists of discrete cations and anions with eight molecules per unit cell. A perspective view of the cation is displayed in Figure 3 along with the atom-numbering scheme. The two copper centers are 6.71 Å apart and are symmetry independent. Table VI lists the bond distances and angles that define the coordination spheres. In many ways the coordinate geometries are similar to those of **1**. The two benzimidazoles and the acetonitrile ligand are the strongly bound ligands. A distorted trigonal pyramid remains the appropriate description of the stereochemistry, but the distortions from ideality are greater than in the carbonyl analogue **1**. Additionally, the crystallographically independent copper centers are less similar to each other. The apical Cu–amine distance at Cu2 is very long (2.72 Å); that for Cu1 is 2.39 Å. The angles about the basal plane show a greater spread from trigonal ideality (101–145°), and the out-of-plane displacements are quite dissimilar (0.09 Å for Cu1 and 0.20 Å for Cu2). A consequence of the basal plane asymmetry at Cu1 is that the longer Cu–amine (Cu2) distance does not correlate with the smaller out-of-plane displacement (Cu1). However, as expected, the metal–ligand bond distances in the basal

(34) Thompson, J. S.; Whitney, J. F. *Inorg. Chem.* **1984**, *23*, 2813.
(35) Villacorta, G. M.; Lippard, S. J. *Inorg. Chem.* **1987**, *26*, 3672.

plane are on average shorter at Cu2, where the apical bond is longer (see Table VI).

Structure of 3. The ligand HCAB-Me differs from HL-Et only in the spacer between the bis(benzimidazole)/amine moieties. The three-atom 2-hydroxypropane spacer is replaced by the five-atom 2,6-methylene-*p*-methylphenol unit. Although the fundamental chelating portion of the ligand is unchanged and the structures of the analogous acetonitrile complexes with HL-Et and HCAB-Me are grossly similar, there are differences in detail that push the coordinate geometry further toward three-coordination in structure **3**.

The X-ray crystal structure of $[Cu_2(HCAB\text{-}Me)(MeCN)_2][CF_3SO_3]_2$ consists of discrete cations and anions with two molecules per unit cell. A perspective view of the cation with the atom-numbering scheme is shown in Figure 4. The two copper centers are 7.99 Å apart and are symmetry independent.

Once again a trigonal-pyramidal description of the geometries at both copper centers is appropriate. The acetonitrile ligand and the two benzimidazoles make up the basal plane in distorted-trigonal arrays similar to those in **2**. However, the apical interactions differ significantly. At Cu1 the apical amine is at the longest distance (2.73 Å) observed for the six copper centers in the three structures **1–3**. That at Cu2 is nearly as long (2.69 Å), where the smallest out-of-plane displacement (0.09 Å) is found. In addition, at Cu2 the sum of the angles subtended by the basal donors (359.5°) is very close to 360°. Thus, the semicoordination of the amine is weakened nearly to the point of overall three-coordination. As we shall see below, this actually occurs in **4**.

The apical interactions at Cu1 present a further oddity. There is the now-familiar weak interaction with the amine nitrogen atom N1 at 2.73 Å. However, there is also a possible weak interaction with the phenolic oxygen atom O1 at 2.90 Å on the same side of the basal plane as N1. Thus, the same overall trigonal-pyramidal description of the geometry is appropriate but the apex is apparently shared in a very unequal manner by two donor atoms rather than one. The significance of the Cu1–phenolic interaction is difficult to judge. It may contribute to the greater out-of-plane displacement at Cu1 (0.18 Å), but the N_{amine}–Cu–$N_{benzimidazole}$ angles, although very acute, are not significantly different from those of Cu2.

The Three-Coordinate Structure of 4. The X-ray crystal structure of $[Cu_2(HL\text{-}H)(MeCN)_2][ClO_4]_2 \cdot {}^1/_3Et_2O$ reveals that the remote change of the benzimidazole substituent from Et to H in HL-H leads to complete loss of the semicoordinated tertiary amine nitrogen donor seen in **1–3**. The structure of **4** contains an H-bonded network of cations and anions with four molecules per unit cell. Figure 5 shows a perspective drawing with the atomic labeling scheme. The central carbon atom of the ligand backbone C1 sits on a crystallographic 2-fold axis relating the two copper atoms. Thus, there is only one independent copper site in the molecule. The copper centers are separated by 12.46 Å as a result of the completely open structure adopted by the binucleating ligand.

The coordinate geometry is approximately trigonal planar. An inspection of bond angles in Table VI reveals coordinate bond angles all within 8° of ideality (120°). They sum to 360° within experimental error. The copper atom is nearly coplanar with the donor atoms, the displacement being only 0.04 Å. The bond lengths to benzimidazole are on average about 0.02 Å shorter than in the nominally four-coordinate species **2** and **3**, as expected for a lower coordination number, but the difference is barely significant. The bond lengths to acetonitrile show no trend.

The amine nitrogen atom N1 is 3.97 Å from the copper atom. The lack of coordination compared to the case for the closely related **1**, **2**, and **3** seems to arise from packing effects and H-bonding effects that occur in HL-H but not in HL-Et or HCAB-Me. The most significant difference between these ligands is the H-bonding capability of the benzimidazole N–H. H-bonding traps the perchlorate ion in a bidentate manner as a bridge between the halves of the molecule. Perchlorate to N–H benzimidazole nitrogen atom distances of 2.89 and 2.97 Å are consistent with good H-bonding. Another packing feature is the intermolecular stacking of benzimidazole rings. The cations are stacked along the *b* axis so that the phenyl rings are parallel and 3.34 (1) Å apart, suggesting some π–π interaction between them. The benzimidazole rings are inclined at an angle of 18.8° to each other and 29.4 and 37.8° relative to the coordinate plane.

There are three reported structures of copper(I) acetonitrile complexes with nitrogen donor binucleating ligands. Two[19,21] are approximately trigonal pyramidal, and the other[17] is approximately tetrahedral. The trigonal array of primary ligands in one of the former has an unspecified apical interaction with its neighboring Cu(MeCN) unit (Cu···Cu = 3.35 Å).[19] The tetrahedrality of the latter can be readily accommodated by the six-membered nature of the chelating rings; the tertiary amine nitrogen atom is 2.15 Å from the copper atom compared to 2.39–3.97 Å in complexes **2–4**, and the copper atom is displaced 0.86 Å from the plane of the bis(pyridine)/acetonitrile donor atoms. If this approximately tetrahedral geometry is viewed in terms of a trigonal pyramid, the present complexes show the effect of an off-normal pulling away of the apical tertiary amine. This is largely the consequence of the five-membered nature of the chelate $N\text{–}(CH_2bzim)_2$ rings (bzim = benzimidazolyl), which are unchanged in the series of ligands HL-Et, HCAB-Me, and HL-H. In **2–4** the different lattices arising from subtle changes in the peripheral substituents and connectivities have enabled us to observe several intermediate positions of the apical donor that would lie on a four- to three-coordinate, tetrahedral to trigonal trajectory.

Conclusions: Relevance to Hemocyanin

In the solid state, the carbonyl structure **1** and the acetonitrile complexes **2** and **3** provide a series of unusually distorted copper(I) geometries that track a gradual off-axis pulling away of the apical ligand from a trigonal-pyramidal coordination geometry. The structure of the three-coordinate **4** represents the completion of this process and the attainment of trigonal coordination. It is the off-normal pulling away of the apical ligand that distinguishes the present work from the more symmetrical process of a tetrahedral to trigonal transition via apical bond elongation along a normal to a trigonal plane. An example of such a more symmetrical intermediate structure can be found in $Cu_2(N4PY2)(OClO_3)_2$, where the perchlorate ion is the apical ligand to a three-N-donor basal plane (Cu–O = 2.55 Å).[17]

One of the more interesting outcomes of this work will be the opportunity to explore how XANES and EXAFS profiles react to the presence of irregular geometries and semicoordinated ligands. To date, the general expectations for two-, three-, and four-coordination in regular geometries are well described and a fair understanding of irregular coordination spheres between two and three has been gained.[15] Much less is known about the XAS and EXAFS fingerprints for geometries between idealized three- and four-coordination.[46] The effects of a CO ligand have also yet to be explored. A good body of knowledge from model compounds will be necessary before XANES and EXAFS methods can be confidently applied to carbon monoxy copper proteins.

Overall, this work confirms the expectation that copper(I) stereochemistries can be many and varied with gross distortions from ideality.[16-21,31,34,35] The distortions can be manifest both in stereochemistry and in bond distances. In synthetic compounds, a surprising array from two- to five-coordination[36] is now known. With even more constrained chelating ligands the plasticity of the copper(I) structure can probably be developed further.

It is clear that proteins are capable of quite dramatic ligand constraints, and it may turn out that copper proteins will offer the best examples of active sites with unusual metal coordination geometries. In the blue copper protein plastocyanin the geometrical arrangement of ligands is far removed from intrinsic, relaxed expectations not only in the copper(I) state but also pointedly so for the copper(II) state.[3] Moreover, the distorted four-coordination to trigonal three-coordination observed in the present work mirrors

(36) (a) Gagne, R. R.; Allison, J. L.; Gall, R. S.; Koval, C. A. *J. Am. Chem. Soc.* **1977**, *99*, 7170. (b) Goodwin, J. A.; Bodager, G. A.; Wilson, L. J.; Stanbury, D. M.; Scheidt, W. R. *Inorg. Chem.* **1989**, *28*, 35.

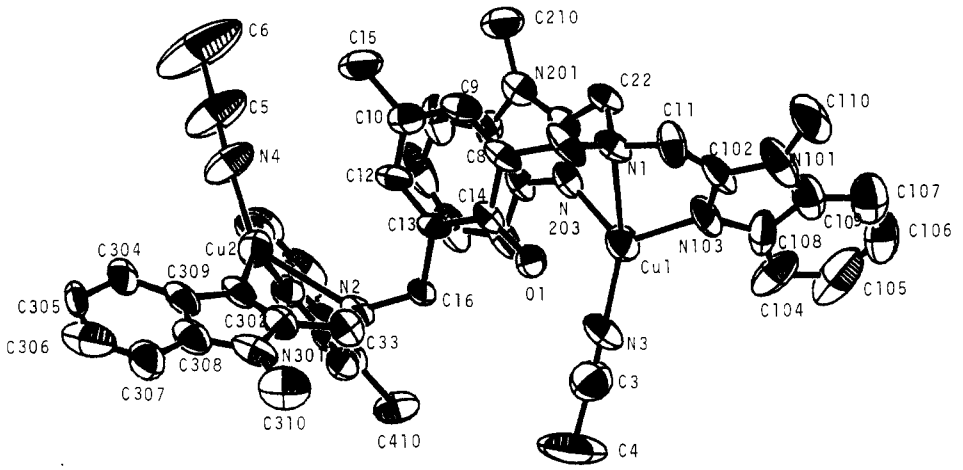

Figure 4. Perspective drawing of the dication of **3**, $[Cu_2(HCAB\text{-}Me)(MeCN)_2]^{2+}$, with thermal ellipsoids contoured at the 50% probability level. See the caption to Figure 1 regarding the numbering pattern.

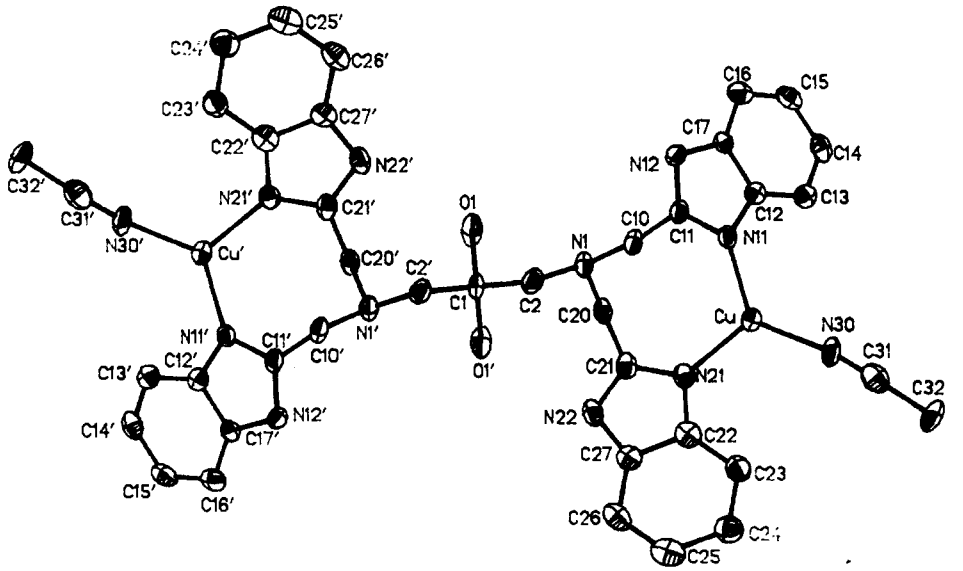

Figure 5. Perspective drawing of the dication of **4**, $[Cu_2(HL\text{-}H)(MeCN)_2]^{2+}$. Omitted from the diagram is the partially occupied ether solvate (C42, C41, O40, C41', C42') and the two perchlorate ions.

the structural change of copper(I) plastocyanin at low pH, where a histidine ligand is lost and trigonal coordination prevails.[3] The X-ray structure of hemocyanin[5] reveals that the binuclear copper active site is buried within a tight helical structure that offers an excellent opportunity for stereochemical control of ligands. The EXAFS interpretation in terms of two-coordination for the copper(I) deoxy form[6] must presumably be taken only as an indication of primary two-coordination by two strongly binding histidines. A third histidine, known to be present from the X-ray structure,[5] may be bound much more weakly, as could a water molecule. The structure of carbon monoxyhemocyanin remains uncertain. The structure of **1** shows that the assumption of tetrahedral four-coordination at the copper site that binds CO does not have to hold; nearly trigonal coordination is a possibility. In either case the enclosure of the two copper atoms in an approximately trigonal-antiprismatic array of six histidines suggests the 1:2 CO:Cu stoichiometry is a result of steric congestion.

Another aspect of the present work that may relate to geometrical constraints in hemocyanin is the lack of reversible dioxygen binding to any of the present copper(I) dinuclear complexes. Even at low temperatures, green, purple, or brown oxygenation products from **1**–**4** form that cannot be deoxygenated by application of a vacuum or N_2 bubbling. There are a number of reasons why this may be occurring, including the presence of oxidatively sensitive benzylic groups[37] or the presence of hydroxylic groups in the ligand backbones, but because the active site of hemocyanin probably contains the same basic functionality as the present model compounds, i.e. imidazoles and water modeled by benzimidazoles and alcohol, we suspect that there are stereochemical restrictions in the protein that are not present in open-chain, dendritic ligands such as HL-Et. The chelating flexibility of HL-Et, and indeed its ability to meet the intrinsic stereochemical requirements of copper(II)[22] rather better than copper(I), suggests that there may be too much driving force for the stabilization of irreversibly formed copper(II) products. Interestingly, the only known reversible dioxygen adducts of copper with significant room-temperature stability have ligand constraints that favor copper(I) over copper(II): tripodal pyrazolylborate ligands in one situation[38,39] and a bulky tetraethylenediamine ligand in the other.[40] Stabilizing copper(I) relative to copper(II) may also help to explain why binucleating ligands with pyridine donors show reversible oxygenation at low temperatures[41] whereas those having a closer biological analogy to histidine (i.e., the stronger donor imidazoles, benzimidazoles, and pyrazoles) do not. Because of this consideration and also because there is probably a copper stereochemical trigger for hemocyanin cooperativity of dioxygen binding,[8] we

(37) Patch, M. G.; McKee, V.; Reed, C. A. *Inorg. Chem.* **1987**, *26*, 776.

(38) Thompson, J. S. *J. Am. Chem. Soc.* **1984**, *106*, 4057.
(39) Kitajima, N.; Koda, T.; Hashimoto, S.; Kitagawa, T.; Moro-oka, Y. *J. Chem. Soc., Chem. Commun.* **1988**, 151.
(40) Thompson, J. S. *J. Am. Chem. Soc.* **1984**, *106*, 8308.
(41) Karlin, K. D.; Cruse, R. W.; Gultneh, Y.; Farooq, A.; Hayes, J. C.; Zubieta, J. *J. Am. Chem. Soc.* **1987**, *109*, 2668.

believe that the precise definition of the coordinate geometry of copper at the active site will be crucial to understanding its functional operation. Also, the subtle changes that allow the dinuclear site to become catalytically active in, for example, tyrosinase and laccase[11,42-44] will also be an interesting outcome of gaining a more precise definition of the active-site structure of hemocyanin and its related binuclear copper proteins.[45]

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Registry No. **1**, 124020-98-0; **2**, 124021-00-7; **3**, 124021-02-9; **4**, 124021-05-2; **5**, 124021-07-4; $[Cu(MeCN)_4]CF_3SO_3$, 58452-28-1; $[Cu(MeCN)_4]ClO_4$, 14057-91-1; $[Cu(MeCN)_4]BF_4$, 15418-29-8.

Supplementary Material Available: Tables S1, S4, S7, and S10 (anisotropic thermal parameters), Tables S2, S5, S8, and S11 (bond distances), and Tables S3, S6, S9, and S12 (bond angles) for compounds **1–4**, respectively (15 pages). Ordering information is given on any current masthead page.

(42) Karlin, K. D.; Gultneh, Y. *Prog. Inorg. Chem.* **1987**, *35*, 219.
(43) Latour, J.-M. *Bull. Soc. Chim. Fr.* **1988**, 508.
(44) Sorrell, T. N. *Tetrahedron* **1989**, *45*, 3.
(45) The structure of the multicopper-containing enzyme ascorbate oxidase has just appeared: Messerschmidt, A.; Rossi, A.; Ladenstein, R.; Huber, R.; Bolognesi, M.; Gatti, G.; Marchesini; Petruzzelli, R.; Finazzi-Agrō, A. *J. Mol. Biol.* **1989**, *206*, 513.
(46) An XAS investigation of copper(I) complexes and copper(I) proteins has just appeared: Blackburn, N. J.; Strange, R. W.; Reedijk, J.; Volbeda, A.; Farooq, A.; Karlin, K. D.; Zubieta, J. *Inorg. Chem.* **1989**, *28*, 1349.

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Equilibrium Constants for the Binding of Aluminum to Human Serum Transferrin

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The binding of aluminum to human serum transferrin in 0.10 M *N*-(2-hydroxyethyl)piperazine-*N'*-ethanesulfonic acid and 5 mM sodium bicarbonate at pH 7.4 has been studied by difference ultraviolet spectrophotometry. Aluminum binding produces peaks at 240 and 288 nm that are characteristic of binding at the transferrin specific metal binding sites. The more intense peak at 240 nm has a molar absorptivity of 14 800 ± 1600 M^{-1} cm^{-1} and has been used to determine two macroscopic aluminum binding constants of log K_1^* = 13.5 ± 0.2 and log K_2^* = 12.5 ± 0.3. Titrations of both forms of monoferric transferrin with Al^{3+} indicate that the larger K_1^* value is associated primarily with Al binding at the C-terminal site and the smaller K_2^* value is associated primarily with the N-terminal site. The Al–transferrin binding constants have been used to include transferrin in the equilibrium distribution of aluminum calculated by using a computer model of serum. This model has been used to evaluate the potential of several low molecular weight ligands for use in decorporation of aluminum.

Aluminum is found at relatively high concentrations in the Earth's crust, in drinking water, in several drugs, and in many processed foods.[1] Until the early 1970s most forms of inorganic aluminum were considered to be virtually nontoxic.[2,3] However, in the past 15 years, several toxic effects of aluminum have been discovered.[2-8] Normally the body maintains low aluminum concentrations through a combination of low intestinal absorption and effective renal clearance. Toxicity is most often observed when the intestinal barrier to aluminum uptake is somehow bypassed. For example, unusually high rates of encephalopathy[3,7-10] and an unusual type of osteomalacic osteodystrophy[2,4,7] among patients on long-term dialysis due to chronic kidney failure have been traced to high aluminum concentrations in the water used for dialysis. Aluminum toxicity is also observed in patients on chronic ambulatory dialysis[11] and on long-term total parenteral nutrition.[12] Aluminum-containing drugs, which are routinely given orally to patients with renal failure to control serum phosphate concentrations, are another source of toxic levels of aluminum in some patients.[4,7,8]

There is also an association between aluminum and Alzheimer's disease, although aluminum does not cause the disease.[13] There is an increase in the aluminum concentration in the brain cells that show the neurofibrillary degeneration characteristic of Alzheimer's disease.[14] The enhanced aluminum concentration may simply be a marker with no relationship to the clinical symptoms. However, it is also possible that the disease may involve metabolic defects that lead to an enhanced susceptibility of certain individuals to chronic aluminum toxicity.[13,15]

Aluminum-induced encephalopathy and osteomalacia associated with long-term dialysis can be treated with the chelating agent desferrioxamine B.[16-20] A primary consideration for any new chelating drug is its ability to remove aluminum from serum proteins, which reportedly bind about 80% of serum aluminum.[8,9,21-23] Fractionation of aluminum in serum has identified

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(1) Lione, A. *J. Environ. Pathol. Toxicol. Oncol.* **1985**, *6*, 21.
(2) Wills, M. R.; Savory, J. *Lancet* **1983**, *No. 2*, 29.
(3) Kerr, D. N. S.; Ward, M. K. In *Metal Ions in Biological Systems*; Marcel Dekker: New York, 1988; Vol. 24, pp 217–258.
(4) Wills, M. R.; Savory, J. In *Chemical Toxicology and Clinical Chemistry of Metals*, Brown, S. S., Savory, J., Eds.; Academic Press: New York, 1983; pp 303–316.
(5) Wisneiwski, H. M.; Sturman, J. A.; Shek, J. W.; Iqbal, K. J. *Environ. Pathol. Toxicol. Oncol.* **1985**, 6, 1.
(6) Alfrey, A. C.; LeGendre, G. R.; Kachny, W. D. *N. Engl. J. Med.* **1976**, 184.
(7) Mayor, G. H.; Lohr, T. O.; Sanchez, T. V.; Burnatowska-Hledin, M. A. *J. Environ. Pathol. Toxicol. Oncol.* **1985**, *6*, 43.
(8) Wills, M. R.; Savory, J. In *Metal Ions in Biological Systems*; Marcel Dekker: New York, 1988; Vol. 24, pp 315–345.
(9) Graf, H.; Stummvol, H. K.; Prager, R.; Luger, A.; Kovarik, J. In *Chemical Toxicology and Clinical Chemistry of Metals*, Brown, S. S., Savory, J., Eds.; Academic Press: New York, 1983; pp 357–360.
(10) O'Hare, J. A.; Murnaghan, D. J. *N. Engl. J. Med.* **1982**, *306*, 654–656.
(11) Salusky, I. B.; Coburn, J. W.; Paunier, L.; Sherrard, D. J.; Fine, R. N. *J. Pediatr.* **1984**, *105*, 717.
(12) Klein, G. L.; Alfrey, A. C.; Miller, N. L.; Sherrard, D. J.; Hazlet, T. K.; Coburn, J. W. *Am. J. Clin. Nutr.* **1982**, *35*, 1425.
(13) Perl, D. P. In *Metal Ions in Biological Systems*; Marcel Dekker: New York, 1988; Vol. 24, pp 259–283.
(14) Perl, D. P.; Brody, A. R. *Science* **1980**, *208*, 297.
(15) Shore, D.; Wyatt, R. J. *Nerv. Ment. Dis.* **1983**, *171*, 553.
(16) Akrill, P.; Ralston, A. J.; Day, J. P.; Hodge, K. C. *Lancet* **1980**, No. 2, 692.
(17) Brown, D. J.; Ham, K. N.; Dawborn, J. K.; Xipell, J. M. *Lancet* **1982**, *No. 2*, 343.
(18) Arze, R. S.; Parkinson, I. S.; Cartlidge, N. E. F.; Britton, P.; Ward, M. K. *Lancet* **1981**, 1116.
(19) Day, J. P.; Ackrill, P.; Garstang, F. M.; Hodge, K. C.; Metcalfe, P. J.; O'Hara, M.; Benzo, Z.; Romero-Martinez, R. A. In *Chemical Toxicology and Clinical Chemistry of Metals*; Brown, S. S., Savory, J., Eds.; Academic Press: New York, 1983; pp 353–356.
(20) Mulluche, H. H.; Smith, A. J.; Abreo, K.; Faugere, M. C. *N. Engl. J. Med.* **1984**, *311*, 140–144.

0020-1669/90/1329-0119$02.50/0