Novel Asymmetric Tripodal Imidazole-containing Ligands forming Dinuclear Copper Compounds through Ligand Sharing

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A novel class of asymmetric imidazole-containing ligands showing dinucleating behaviour is reported: ligand **1** forms a dinuclear complex with copper(II) perchlorate in which each of the two ligands is shared by the two Cu(II) ions.

In the dinuclear type-3 site of the copper protein haemocyanin, each copper ion is bound by three imidazole nitrogens from histidine residues. The crystal structures of both the oxy and deoxy form of Limulus lyphemus haemocyanin have been determined.[1] The Cu–Cu distance in the oxy form has been reported to be 3.6 Å, and is *ca.* 4.6 Å in the deoxy form. The ligands most frequently used in biomimetic studies for the type-3 active site of copper proteins are benzimidazoles, pyrazoles and pyridines.[2,3] Because of the presence of histidine as a ligand to copper ions in almost all copper proteins,[4] copper complexes with the biologically more relevant imidazolyl donors are increasingly being studied as model compounds for copper protein active sites.[5,6]

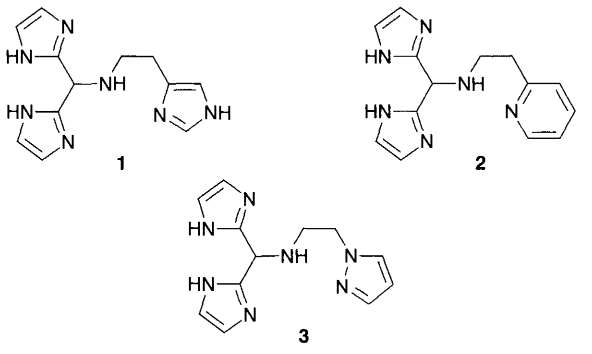

Fig. 1 Schematic drawing of the ligands **1**, **2** and **3**

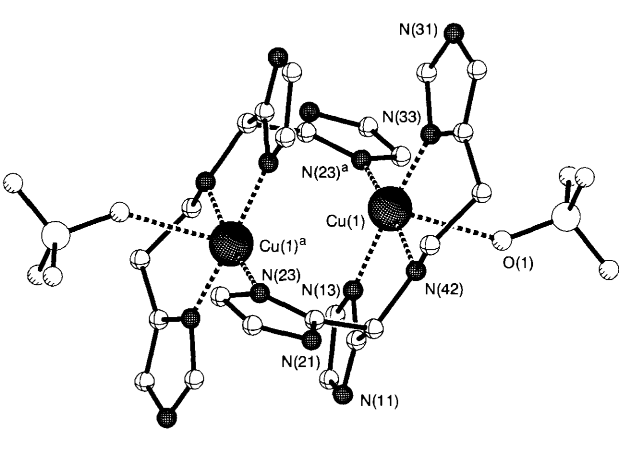

Fig. 2 Molecular structure of the dinuclear copper complex **4** {[Cu-$_2$(**1**)$_2$(ClO$_4$)$_2$](ClO$_4$)$_2$}. Hydrogen atoms and non-coordinated perchlorate anions have been omitted for clarity. Only the major disorder component of the coordinated perchlorate anions is shown. Selected bond distances (Å) and angles (°): Cu(1)–N(13) 1.980(3), Cu(1)–N(42), 2.060(3), Cu(1)–N(33) 1.954(3), Cu(1)–N(23)^a 2.004(3), Cu(1)–O(1) 2.563(3), Cu(1)–Cu(1)^a 3.4229(6), O(1)–Cu(1)–N(13) 90.88(11), N(13)–Cu(1)–N(42) 80.91(12), O(1)–Cu(1)–N(33) 87.88(11), N(13)–Cu(1)–N(23)^a 91.16(12), O(1)–Cu(1)–N(42) 81.94(11), N(23)^a–Cu(1)–N(33) 95.14(12), O(1)–Cu(1)–N(23)^a 97.29(11), N(33)–Cu(1)–N(42) 92.79(12). (^{a} Denotes symmetry operation $-x$, $-y$, $-z$.)

In the present study, three new asymmetric tripodal imidazole-containing ligands **1**, **2** and **3** have been designed and synthesized[7,8] by the reaction of bis(imidazol-2-yl)nitromethane with histamine, 2-ethylaminopyridine and 1-ethylaminopyrazole, respectively.† Reaction of **1** with copper(II) perchlorate in ethanol results in the formation of a quite unusual dinuclear complex **4** {[Cu$_2$(**1**)$_2$(ClO$_4$)$_2$](ClO$_4$)$_2$}, which is formed by the sharing of two ligands by the two copper ions.‡ The sharing of two ligands in the present complex creates a cavity between the two Cu^{II} ions. A space-filling model of this dinuclear compound shows that after a slight conformational rearrangement the cavity is accessible for small molecules and anions.

Structural analysis§ of **4** shows that the copper ions are coordinated in a square-pyramidal geometry. In the equatorial plane, each copper ion is coordinated by one of the imidazole nitrogens N(13) from the bis(imidazole) unit, the amine nitrogen N(42) and the nitrogen of the separate imidazole group N(33), while the fourth coordinated nitrogen N(23)^a is from an imidazole group provided by the bis(imidazole) unit of another ligand. The resulting Cu–Cu distance is 3.42 Å. Each copper ion is weakly coordinated at the axial position by a perchlorate anion with a Cu–O distance of 2.56 Å. The diffuse–reflectance spectrum in the VIS–NIR region of **4** shows a band at 17.7 × 10^3 cm^{-1}, which is in the usual range for square-pyramidal coordinated Cu^{II}.[9] EPR spectra of the polycrystalline powder recorded at room temperature and 77 K show a typical axial triplet spectrum[10] with $g_\perp$ = 2.02, $g_\parallel$ = 2.21 and D = 0.058 cm^{-1}. The same triplet spectrum is also obtained from a frozen solution of **4** in methanol–toluene, proving that the dinuclearity of this complex is preserved in methanolic solutions.

This communication only deals with the structure and spectroscopy of a representative example of a dinuclear Cu^{II} compound with the ligand **1**. Preliminary EPR studies show that dinuclear complexes similar to **4** are formed with the ligands **2** and **3**. Studies towards the structure and the reactivity of the Cu^{I} and Cu^{II} complexes with all three ligands are ongoing.

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Footnotes

† *Selected spectral data* for **1**, **2** and **3**. (The three ligands were characterised on the basis of their ^{1}H NMR spectra). ^{1}H NMR (200 MHz, CD$_3$OD, 25 °C, δ 0–10) for **1**, bis(1,1′-imidazol-2-yl)[4-imidazol-4(5)-yl]-2-aza-butane (biib): δ 7.54 (s, 1H, Im-*H*), 6.99 (s, 4H, Im-*H*), 6.76 (s, 1H, Im-*H*), 5.13 (s, 1H, C*H*), 2.76 [s (br), 4H, C*H*$_2$, C*H*$_2$]. For **2**, bis(1,1′-imidazol-2-yl)(4-

pyridine-2-yl)-2-aza-butane (bipyb): δ 8.42 (d, 1H, py-*H*), 7.76 (t, 1H, py-*H*), 7.29 (m, 1H, py-*H*) 6.98 (s, 4H, Im-*H*), 5.17 (s, 1H, C*H*), 2.91 (m, 4H, CH_2, CH_2). For **3** bis(1,1′-imidazol-2-yl) [4-(pyrazole-1-yl)]-2-aza-butane (bipab): δ 7.55 (d, 1H, Py-*H*), 7.40, (d, 1H, Py-*H*), 6.88 (s, 4H, Im-*H*), 6.18 (s, 1H, C-*H*), 5.95 (t, 1H, py-*H*), 4.15 (t, 2H, CH_2), 2.85 (t, 2H, CH_2).

‡ Related coordination behaviour of tripodal ligands has been reported in some Cu^I complexes.[5]

§ *Crystal data* for **4**, $C_{24}H_{30}Cl_2Cu_2N_{14}O_8 \cdot 2ClO_4 \cdot 2H_2O$, monoclinic, space group $P2_1/c$ (No. 14), a = 10.9947(4), b = 9.0029(4), c = 21.5198(9) Å, β = 115.235(3)°, V = 1926.84(14) Å^3, Z = 2, D_x = 1.854 g cm^{-3}, F(000) = 1092, μ(Mo-Kα) = 48.0 cm^{-1}, 8944 reflections measured, 3981 independent, R_{int} = 0.043, ($2.3 < \theta < 27.50°$, $\omega/2\theta$ scan, $\Delta\omega = 0.60 + 0.14 \tan(\theta)°$, T = 295 K, Cu-Kα radiation, Ni filter, λ = 1.54184 Å) on an Enraf-Nonius CAD4F diffractometer. Data were corrected for Lorentz polarisation and for a linear decay of 3%; empirical absorption correction applied (DIFABS, correction range 0.856–1.253). The structure was solved by automated Patterson methods (DIRDIF92). Refinement on F was carried out by full-matrix least-squares techniques (SHELX76); final R value 0.043, wR = 0.050, w = $1/[\sigma^2(F) + 0.000134 F^2]$, S = 1.07, for 331 parameters and 3478 reflections with $I > 2.5\sigma(I)$. Hydrogen atoms were included in the refinement in calculated positions (C–H = 0.98 Å) riding on their carrier atoms, except for the water hydrogen atoms, which were located on a difference Fourier map and subsequently included in the refinement. Both the coordinated and the free ClO_4^- ions are disordered around a Cl–O bond. All non-hydrogen atoms were refined with anisotropic thermal parameters, except for the minor disorder component of the coordinated ClO_4^- ion; the hydrogen atoms were refined with an overall isotropic thermal parameter of 0.062(3) Å^2. A final difference Fourier map showed no residual density outside −0.47 and 0.61 e Å^{-3}. Atomic coordinates, bond lengths and angles, and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre. See Information for Authors, Issue No. 1.

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