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A phenoxyl radical complex of copper(II)†

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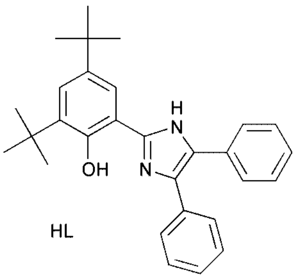
A new *N,O*-bidentate pro-ligand (HL), [ML$_2$] (M = Cu, Zn) and [CuL$_2$][BF$_4$] have been synthesised; [CuL$_2$]·4DMF and [CuL$_2$][BF$_4$]·2CH$_2$Cl$_2$ have been crystallographically and spectroscopically characterised; these data indicate that [CuL$_2$]$^+$ cations are constituted as [Cu^{2+}(L$^\cdot$)(L$^-$)]$^+$ and involve the phenoxyl radical L$^\cdot$.

Galactose oxidase (GAO)[1–3] and glyoxal oxidase (GLO)[4] belong to an emerging and important class of metalloenzymes that involve an organic radical as an integral component of their active site.[5] The active form of the catalytic site of both GAO and GLO involves Cu^{II} ligated by a thioether-modified tyrosinyl radical. This centre is responsible for a two-electron oxidation of the substrate;[1–7] *e.g.* GAO converts a primary alcohol to the corresponding aldehyde with the concomitant reduction of O$_2$ to H$_2$O$_2$. Considerable progress has been made in the development of chemical analogues of the active site of GAO, including several examples of complexes that contain Cu^{II} bound to a phenoxyl radical.[8,9] However, such species have eluded crystallographic characterisation.

Inspired by the nature of the catalytic centres of GAO and GLO, the new *N,O*-bidentate pro-ligand 2-[2′-(4′,6′-di-*tert*-butylhydroxyphenyl)]-4,5-diphenylimidazole (HL) was designed. To enhance the possibility of isolating complexes of L$^\cdot$, HL contains no readily oxidisable functionality, other than the phenol group. Also, the 2,4-^{t}Bu groups block pathways for decomposition of the phenoxyl radical state and could stabilise this state by a +I effect.



HL

HL was synthesised by the condensation of 3,5-di-*tert*-butylhydroxybenzaldehyde with benzil (1:1) in AcOH in the presence of an excess of NH$_4$OAc (yield 75%). The UV–VIS spectrum of HL in CH$_2$Cl$_2$ at 0 °C contains absorptions at λ_{max} 228 nm (ε = 36500 M^{-1} cm^{-1}), 296 (21800) and 325 (25200). The cyclic voltammogram of HL, at room temperature in CH$_2$Cl$_2$, exhibits a reversible one-electron oxidation at 0.43 ($E_{½}$/V *vs.* Fc$^+$/Fc, Fig. S1, ESI†). Electrochemical oxidation of HL in CH$_2$Cl$_2$ at −40 °C in an OTTLE cell produced new absorptions at λ_{max} 379 nm (ε = 9700 M^{-1} cm^{-1}), 401 (9200), 514 (4000) and 715 (5600); the band at 401 nm is typical of a π–π* transition of a phenoxyl radical.[10] The X-band EPR spectrum of the species generated by electrochemical oxidation of HL in CH$_2$Cl$_2$ (recorded at 110 K) consisted of a single resonance, g_{iso} = 2.004 (line width, 10 G).

The reaction of Cu(BF$_4$)$_2$·H$_2$O with HL (1:2) in MeOH yielded a brown solution that became deep green upon addition of Et$_3$N. Slow evaporation of this solution in air produced purple–brown crystals of [CuL$_2$] (**1**) (yield 85%); orange crystals of [CuL$_2$]·4DMF (**1**·4DMF) were obtained by the slow evaporation of a solution of **1** in CH$_2$Cl$_2$–DMF (9:1 v/v). [ZnL$_2$] (**2**) was synthesised in a similar manner, from Zn(BF$_4$)$_2$·H$_2$O and HL (1:2). Compounds **1** and **2** each exhibit two reversible, one-electron oxidations at 0.17, 0.51 (**1**) and 0.23, 0.51 (**2**) ($E_{1/2}$/V *vs.* Fc$^+$/Fc) (Fig. S1, ESI†). The close correspondence between the electrochemical properties of **1** and **2** implies that each oxidation is ligand-based.

Oxidation of **1** by Ag[BF$_4$] (1:1) in CH$_2$Cl$_2$ produced an intensely green coloured product, [**1**][BF$_4$]·2CH$_2$Cl$_2$ (yield 85%), single crystals of which were obtained by recrystallisation from CH$_2$Cl$_2$–hexane (1:4 v/v).

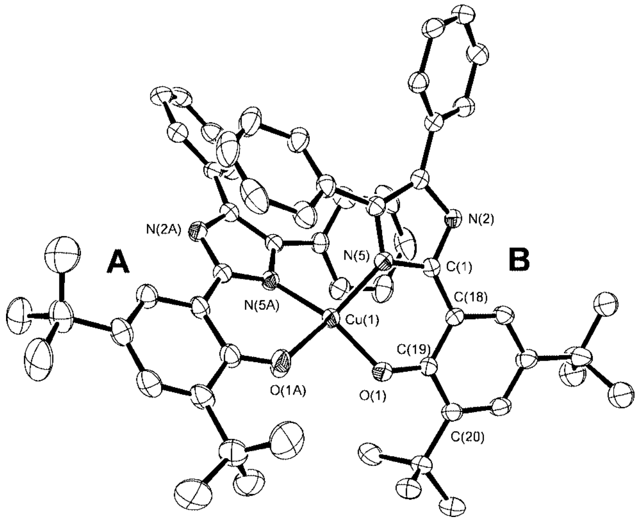


Fig. 1 ORTEP representation of the cation of [**1**][BF$_4$]·2CH$_2$Cl$_2$.

The X-ray crystallographic characterisations‡ of **1**·4DMF and [**1**][BF$_4$]·2CH$_2$Cl$_2$ have shown that each compound contains a copper centre with a distorted tetrahedral N$_2$O$_2$-coordination sphere. The two ligands of **1**·4DMF are related by a C_2-axis, but the two ligands of the cation of [**1**][BF$_4$]·2CH$_2$Cl$_2$ are structurally inequivalent (L^A and L^B; Figs. 1 and 2). For L^B, the length of each C–C, C–O and C–N bond is similar to that of the corresponding bond of **1**. However, for L^A the C–O distance is significantly *shorter* and the two adjacent C–C bonds are significantly *longer* than the corresponding bonds of both **1** and L^B. Also, the Cu–O bond involving L^A is significantly *longer* than that in **1**, but each of the other three metal–ligand bonds in [**1**]$^+$ is significantly *shorter* than its counterpart in **1**. This

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† Electronic supplementary information (ESI) available: synthesis and characterisation of HL, **1**, [**1**][BF$_4$] and **2**; crystallographic data for **1**·4DMF, and details of electrochemical experiments. See http://www.rsc.org/suppdata/cc/b1/b105186p/

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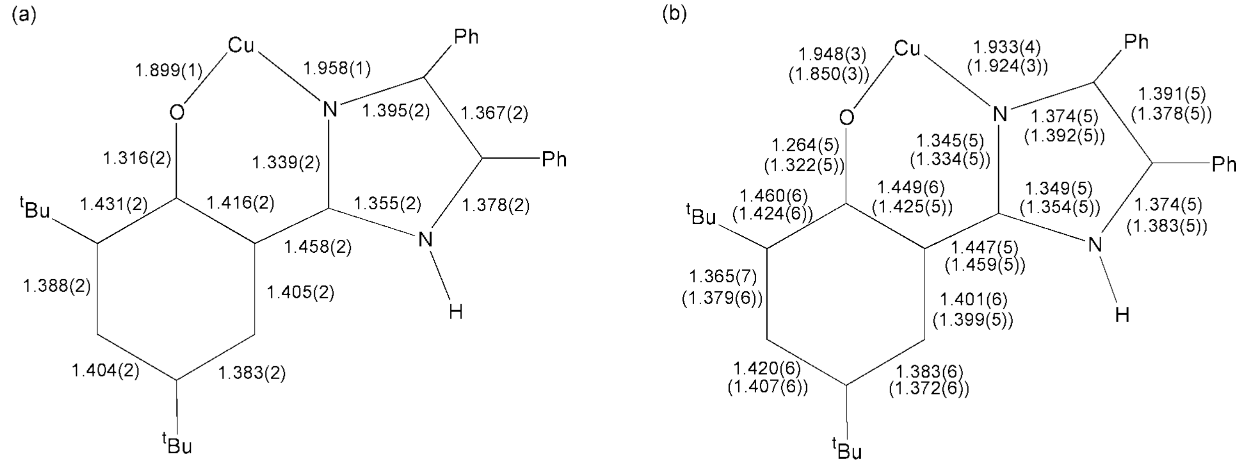

Fig. 2 Selected bond lengths of (a) **1**·4DMF, in which the two ligands are related by a C_2 axis and (b) the cation of [**1**][BF_4]·$2CH_2Cl_2$ containing L^A and L^B (values for the latter are given in parentheses).

structural information is taken to indicate that [**1**]$^+$ contains both a phenoxyl radical ($L^A = L^\cdot$) and a phenolate ($L^B = L^-$) ligand coordinated to Cu^{II}; *i.e.* [**1**]$^+$ is constituted as $[Cu^{2+}(L^\cdot)(L^-)]^+$. Thus, the oxidation of a phenolate ligand in **1** to a phenoxyl group in [**1**]$^+$ is accompanied by a shortening of the C–O bond and a lengthening of the Cu–O bond. This observation is consistent with the structural information obtained[11] for a complex of Cr^{III} that contains one phenoxyl radical and two phenolate ligands, in which the C–O distance in the phenoxyl radical is 1.290(4) Å. The C–O distance of L^A is 1.264(5) Å, emphasising the C=O character of this bond. The length of the C–O and C–C bonds of L^A, in comparison with those of L^B and the phenolate ligands of **1**, are in accord with an electronic structure described by the two resonance forms of Fig. 3, *i.e.* the unpaired electron of the phenoxyl group is delocalised over both *ortho* positions.

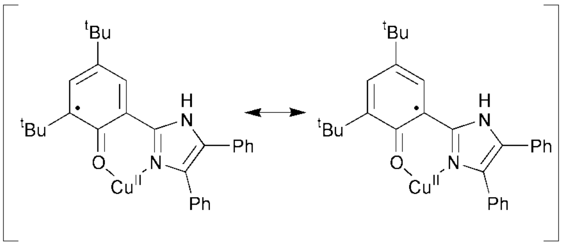

Fig. 3 Resonance forms of $L^\cdot$ in $[Cu^{2+}(L^\cdot)(L^-)][BF_4]$.

1 and [**1**][BF_4] display identical cyclic voltammograms in CH_2Cl_2 and the UV–VIS spectrum of [**1**][BF_4] is the same as that obtained for [**1**]$^+$ generated electrochemically. The OTTLE spectra, (Fig. S2, ESI†) recorded for the oxidation of **1** in CH_2Cl_2 at 0 °C show that this process produces an absorption at 410 nm that is assigned to a π–π* transition of the phenoxyl radical (L) bound to Cu^{II}.[8,9]

The EPR spectrum of **1** in CH_2Cl_2–toluene (9:1) at 116 K, (Fig. S3, ESI†) is typical of a rhombic Cu(II) ($S = 1/2, I = 3/2$) complex with a $(d_{x^2-y^2})^1$ (or $(d_{xy})^1$) ground state: $g_{xx} = 2.053$, $g_{yy} = 2.047$, $g_{zz} = 2.253$. In contrast, [**1**][BF_4] in CH_2Cl_2 at 77 K at X-band over the range 0–6000 G was found to be essentially EPR silent. The temperature dependence (3–320 K) of the magnetic susceptibility of [**1**][BF_4] (Fig. S4, ESI†) has been modelled by the Hamiltonian $H = -2JS_{Cu}S_{rad}$, where $J = -6.1$ cm^{-1} and $S_{Cu} = S_{rad} = 1/2$, $g_{Cu} = 2.12$, $g_{rad} = 2.00$. [**1**][BF_4] possesses a diamagnetic ground state ($S = 0$) that is considered to arise from an antiferromagnetic coupling between the unpaired electron of the Cu(II) and the unpaired electron of the coordinated phenoxyl radical, $L^\cdot$.

Thus, oxidation of $[CuL_2]$ is ligand-based and produces a cation that is constituted as $[Cu^{2+}(L^\cdot)(L^-)]^+$, involving Cu^{II} bound to both a phenoxyl radical ($L^\cdot$) and a phenolate (L^-) ligand. The crystallographic information obtained for [**1**][BF_4]·$2CH_2Cl_2$ have been crucial to this assignment[12] and the UV–VIS, EPR and magnetic susceptibility data recorded for [**1**][BF_4] provide additional and independent support for this proposal. This study represents the first structural characterisation of a phenoxyl radical bound to Cu^{II}, a chemical combination that is crucial for the catalytic activity of GAO and GLO.

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Notes and references

‡ *Crystal data* for [**1**][BF_4]·$2CH_2Cl_2$: $C_{60}H_{66}N_4O_2BF_4Cl_4Cu$, dark green square plate, $M = 1167.3$, monoclinic, space group $P2_1/n$, $a = 12.6062(7)$, $b = 18.2942(10)$, $c = 25.5061(14)$ Å, $\beta = 96.191(1)°$, $V = 5847.9(9)$ Å^3, $Z = 4$, $D_c = 1.326$ g cm^{-3}, $T = 150(2)$ K, $F(000) = 2432$, μ(Mo-Kα) = 0.61 mm^{-1}, 40636 reflections collected, 14159 unique ($R_{int} = 0.053$). The final agreement factors are $R_1 = 0.068$ for 8068 data with $F > 4\sigma(F)$ and $R_1 = 0.125$, $wR_2 = 0.189$ for 13749 data. The CH_2Cl_2, BF_4 and one ${}^tBu$ group exhibited disorder which, in each case, was modelled over two sites with suitable geometric restraints applied. CCDC reference numbers 167603 and 167604. See http://www.rsc.org/suppdata/cc/b1/b105186/ for crystallographic data in CIF or other electronic format.

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