Crystallographic Characterization of Octaethylverdohaem

Alan L. Balch,* Richard Koerner and Marilyn M. Olmstead

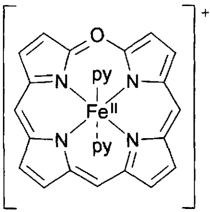
Department of Chemistry, University of California, Davis, California 95616, USA

The green product of coupled oxidation of octaethylporphyriniron(II) in pyridine has been determined by X-ray crystallography to be the low-spin (diamagnetic) bis(pyridine)iron(II) complex of the octaethyloxaporphyrin anion.

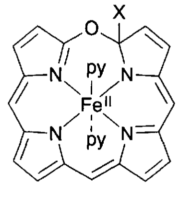
The coupled oxidation of haems in pyridine solution with dioxygen as oxidant and either ascorbic acid or hydrazine as reductant produces a diamagnetic green pigment, verdohaem.[1–5] Two formulations, **A** and **B**, have been given for this compound, but the preponderance of recent evidence has indicated that structure **A** is correct.[3,4] Nevertheless, the structural details of the iron coordination and the axial ligation for the verdohaems have not been directly ascertained. The coupled oxidation process is especially important because it has been widely employed as a model for haem catabolism.[2,6] This process converts haem into biliverdin through the enzyme haem oxygenase. Biliverdin is subsequently reduced by biliverdin reductase to form bilirubin. We now report on the isolation of a crystalline salt of the verdohaem derived from the symmetrical porphyrin [(py)$_2$Fe^{II}(oep)] (H$_2$oep = octaethylporphyrin). The X-ray structural study of this salt, [(py)$_2$Fe^{II}(oeop)](PF$_6$) (oeop = octaethyloxaporphyrin), has allowed the thorough characterization of the axial ligation of the iron and the macrocycle.

Octaethylverdohaem in the form of [(py)$_2$Fe^{II}(oeop)]Cl was obtained as described previously,[4] and converted into the hexafluorophosphate salt by treatment of a dioxygen-free dichloromethane solution of the green complex with a dioxygen-free methanolic solution of ammonium hexafluorophosphate (Scheme 1). The resulting solution was evaporated to dryness, and the residue dissolved in a minimum volume of dichloromethane. Filtration and evaporation of the solution yielded solid [(py)$_2$Fe^{II}(oeop)](PF$_6$) which was crystallized by the addition of diethyl ether to a pyridine solution of the compound. While [(py)$_2$Fe^{II}(oeop)](PF$_6$) forms deep red crystals, these crystals dissolve in pyridine or dichloromethane to form green solutions which show the characteristic UV–VIS [λ_{max}/nm (ε/dm^3 mol^{-1} cm^{-1}) in pyridine solution: 388 (4.4×10^4), 494 (5.8×10^3), 526 (1.0×10^4), 652 (3.4×10^4)] and ^{1}H NMR [in (CDCl$_3$): δ 9.10 (2, relative integrated intensity), 8.68(1), *meso* protons; 3.62, 3.49, 3.48, 3.39 (each 4), methylene protons; 1.69, 1.67, 1.63, 1.56 (each 6), methyl protons] spectra of octaethylverdohaem.[3,4] The UV–VIS spectra of the hexafluorophosphate and chloride salts in pyridine are similar and the spectrum of the chloride salt is unaffected by the addition of a tenfold excess of chloride ion in the form of benzyl(trimethyl)ammonium chloride. These observations, along with the fact that electrical conductivity studies (in 5% pyridine–nitromethane) show that solutions of both the chloride (Λ_M = 105 S cm^2 mol^{-1}) and the hexafluorophosphate (Λ_M = 142 S cm^2 mol^{-1}) are 1 : 1 electrolytes, are consistent with structure **A** for both forms with either a coordinating or a non-coordinating counter-ion.

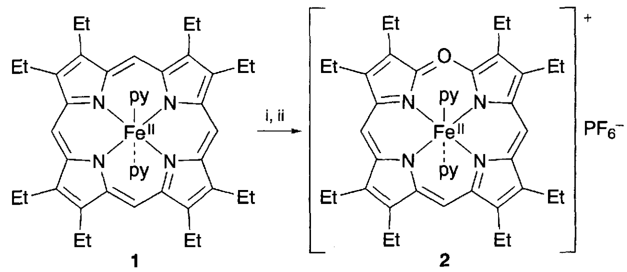
The results of an X-ray diffraction study of this salt are shown in Fig. 1.† The solid consists of the complex cation and a hexafluorophosphate ion with no unusual contacts between these units. The iron ion in the cation and the phosphorus ion in the anion are located at centres of symmetry. Within the cation, the iron is six-coordinate with bonds to the four nitrogen atoms of the macrocycle and to the nitrogen atoms of the two axial pyridine ligands. The two independent in-plane Fe–N distances are similar [Fe–N(1) 1.977(6), Fe–N(2) 1.966(5) Å], while the axial Fe–N distance [Fe–N(3), 2.029(6) Å] is slightly longer. These distances are consistent with the presence of low-spin iron(II) in the cation.[7–10] For example, in [(py)$_2$Fe^{II}(tpp)][9] (tpp = tetraphenylporphyrin dianion), the in-plane Fe–N(tpp) distance is 1.993(6) Å and the axial Fe–N(py) distance is 2.039(1) Å. For iron(II) complexes, the trend in axial Fe–N distances (bond to imidazole[7] shorter than to pyridine[9] which is shorter than to piperidine[8]) correlates with the steric properties of the axial ligand. The pyridine ligands are parallel to one another and nearly eclipse the *meso* carbon atoms. The C(1)–Fe–N(3)–C(18) dihedral angle is 1.5°. In [(py)$_2$Fe^{II}(tpp)] the corresponding angle is 11.1°.[9] There is no group added to the macrocycle, and thus the old formulation of verdohaem as **B** is incorrect. The macrocycle, excluding the peripheral ethyl groups, is flat as the formal diagram shown in Fig. 2 demonstrates. As is frequently the case with core-modified porphyrins,[4] there is disorder in the location of the oxygen atom. This atom has occupancies of 0.30(3) at the site denoted in Fig. 1 as O(1) and the corresponding site generated by the centre of



A



B



Scheme 1 *Reagents and conditions*: i, O$_2$ in pyridine–dichloromethane, ascorbic acid; ii, ammonium hexafluorophosphate

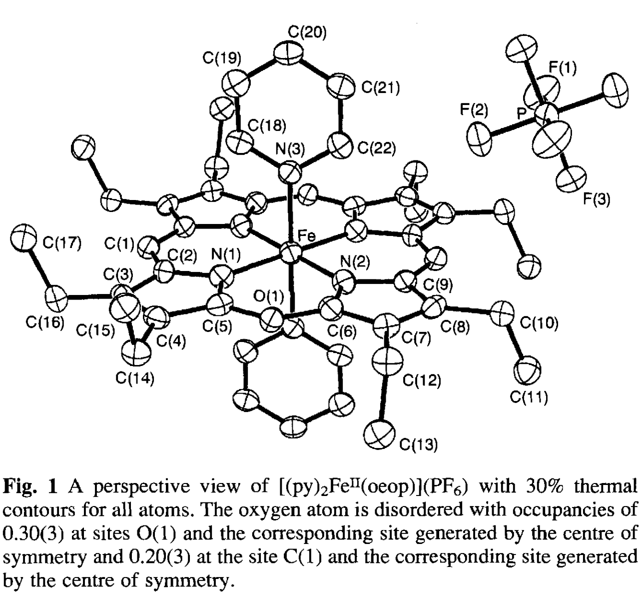


Fig. 1 A perspective view of [(py)$_2$Fe^{II}(oeop)](PF$_6$) with 30% thermal contours for all atoms. The oxygen atom is disordered with occupancies of 0.30(3) at sites O(1) and the corresponding site generated by the centre of symmetry and 0.20(3) at the site C(1) and the corresponding site generated by the centre of symmetry.

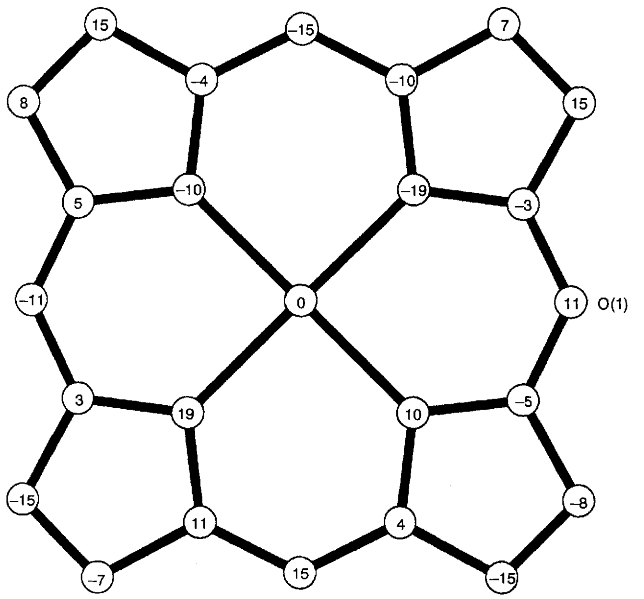
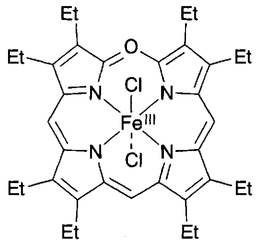


Fig. 2 A diagram of the oxaporphyrin core of $[(py)_2Fe^{II}(oeop)]^+$ in which the out-of-plane displacements (in units of 0.001 Å) are shown for each atom



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symmetry, and 0.20(3) at the site denoted as C(1) and its symmetry-generated counterpart.

The availability of this structurally characterized verdohaem presented the opportunity to examine its redox behaviour electrochemically and to ascertain why an iron(II) rather than an iron(III) complex was obtained in the coupled oxidation process. A previous electrochemical study had described the one-electron reduction of octaethylverdohaem but had not examined the oxidation of the cation. In agreement with Tajima *et al.*,[11] we find a one-electron reduction in dimethylformamide–pyridine (6:4, *v*/*v*) with 0.1 mol dm^{-3} tetrabutylammonium perchlorate as supporting electrolyte at −1.07 V *vs.* a silver/silver chloride electrode, but we also see a quasi-reversible one-electron oxidation at 0.16 V with i_a/i_c = 2.9. In dichloromethane with 10% pyridine and 0.1 mol dm^{-3} tetrabutylammonium perchlorate as supporting electrolyte the process occurs at 0.28 V *vs.* a silver/silver chloride electrode and is more nearly reversible with i_a/i_c = 1.2 (for reference, the oxidation of ferrocene occurs at 0.17 V in this solvent system). The oxidation product, however, is chemically unstable. Attempts to chemically oxidize pyridine solutions of $[(py)_2Fe^{II}(oeop)](PF_6)$ with bromine or thianthrene radical cation have left the complex intact. Apparently the oxidation product is reduced in the presence of pyridine to verdohaem. In support of that, we find that dissolution of the iron(III) complex, **3**,[4] in pyridine rapidly results in reduction and axial ligand displacement with $[(py)_2Fe^{II}(oeop)]^+$ as the product as shown by the observation of its characteristic UV–VIS spectrum. Similar reductions of iron(III) porphyrins in amine solvents such as pyridine and piperidine have previously been seen.[12]

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Footnote

† *Crystal data*: dark red parallelepipeds of $[C_{45}H_{53}FeN_6O](PF_6)$ that were obtained by diffusion of diethyl ether into a pyridine solution of the compound form in the triclinic space group $P\bar{1}$, with a = 9.772(3), b = 10.938(3), c = 11.083(4) Å, α = 75.71(3), β = 64.58(2) and γ = 86.21(2)° at 130 K with Z = 1 with the use of nickel-monochromated Cu-Kα (λ = 1.54178 Å) radiation. Refinement of all reflections with 273 parameters and ten restraints yielded $wR2$ = 0.198 based on F^2 and a conventional R_1 = 0.075 based on 1856 reflections with $I > 2\sigma(I)$. 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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