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The structures of recently discovered non-heme oxoiron(ιv) complexes of two pentadentate ligands have been deduced, one by X-ray crystallography and the other by ¹H NMR spectroscopy. Detailed experimental and theoretical studies are described by L. Que, Jr., C. J. Cramer et al. on the following pages.

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Oxoiron(IV) Complexes

Structures of Nonheme Oxoiron(IV) Complexes from X-ray Crystallography, NMR Spectroscopy, and DFT Calculations**

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Oxoiron(IV) species are frequently invoked as reactive intermediates in the oxygen-activation mechanisms of mononuclear nonheme iron enzymes.^[1] In 2003, the trapping of the first nonheme oxoiron(IV) intermediate in the reaction of O2 with the 2-oxoglutarate-dependent enzyme TauD, which was complexed with 2-oxoglutarate and its substrate taurine, was reported.^[2-5] Contemporaneously, the first examples of wellcharacterized synthetic oxoiron(IV) complexes with nonheme ligand environments were also described.^[6,7] The presumably reactive oxoiron(IV) units could be stabilized sufficiently by tetraaza ligands such as macrocyclic tetramethylcyclam (TMC) and tripodal tris(2-pyridylmethyl)amine (TPA) to allow their spectroscopic characterization at low temperature. In the case of the TMC complex, its considerable stability allowed it to be crystallized and its structure to be determined by X-ray crystallography. These results represented the first high-resolution structural data for any oxoiron(IV) complex, heme or nonheme. Subsequently it was found that the oxoiron(IV) unit could also be generated from precursor iron(II) complexes of pentadentate pentaaza ligands such as N,N-bis(2-pyridylmethyl)-N-bis(2-pyridyl)methylamine

(N4Py) and N-benzyl-N,N',N'-tris(2-pyridylmethyl)-1,2-diaminoethane (Bn-TPEN) by treatment with a peracid or PhIO. In fact, $[Fe^{IV}(O)(N4Py)]^{2+}$ (1) and $[Fe^{IV}(O)(Bn-$ TPEN]²⁺ (2) could be produced in high yields at room temperature by reaction with excess solid iodosylbenzene in CH₃CN to afford solutions with significant thermal stability.^[8] Herein, we report insight into the structures of 1 and 2 obtained from a combination of X-ray crystallography, NMR

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spectroscopy, and DFT (density functional theory) calculations, and their relative thermal stabilities.

Complexes 1 and 2 exhibit half-lives of approximately 60 and 6 h, respectively, at room temperature. The greater thermal stability of 1 allowed the isolation of single crystals for X-ray crystal structural analysis (Figure 1) to provide only



Figure 1. Molecular structure of 1 (a) and top views of space-filling models of 1 (b) and 3 (c). Metal-ligand bond lengths [Å] for 1: Fe-O 1.639(5), Fe-N1 2.033(8), Fe-N2 1.964(5), Fe-N3 1.949(5).

the second high-resolution structure of an oxoiron(IV) complex. The X-ray crystal structure of 1 shows an Fe-O bond length of 1.639(5) Å, a value that is essentially identical to the length of 1.646(3) Å reported for the analogous bond in $[Fe(O)(TMC)(NCCH_3)](SO_3CF_3)_2$ (3).^[6] Trans to the oxo ligand in 1 is the amine nitrogen atom that holds the pentadentate ligand together, with an Fe-N1 bond length of 2.033(8) Å, the longest metal-ligand bond in the molecule. The O1, Fe, and N1 atoms are nearly colinear with an O1-Fe-N1 angle of 178.6(3)°. Coordinated in the equatorial plane are the four pyridine nitrogen atoms, whose rings are aligned parallel to the Fe-O axis, and the iron atom lies 0.252 Å above the plane subtended by these four pyridyl nitrogen atoms towards the oxo ligand. Interestingly, the equatorial Fe-N bond lengths are on average 1.957(5) Å; these bonds are shorter than the corresponding equatorial bonds in 3 by 0.1 Å and reflect the stronger bonding ability of a pyridine moiety relative to a tertiary amine.

Figures 1b and c compare the top views of space-filling models of 1 and 3 and reveal a large difference in the accessibility of the oxoiron unit in the two complexes. Whereas the hydrogen atoms of the TMC macrocycle nestle nicely around the oxo atom in $\mathbf{3}$ and restrict access,^[6] the oxo group in 1 is much more exposed not only from the top of the molecule but also along channels that form between adjacent pyridine rings. This difference may rationalize the relative reactivities of the two complexes. While 3 is quite inert toward hydrocarbon substrates, at room temperature 1 can attack C-H bonds as strong as those in cyclohexane.^[6,8]

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Single crystals of **2** have not yet been isolated, so its structure must be deduced by alternative means. A recent EXAFS (extended X-ray absorption fine spectrum) study^[9] revealed the presence of a short Fe–O bond of 1.67 Å and Fe–N bond lengths that average 2.00 Å, as expected, but no insight was gained into how the pentadentate ligand wraps around the metal center. The flexibility of the ligand requires three conformational isomers, if we neglect enantiomers, to be considered (Figure 2). Isomer **A** contains two pyridine rings that eclipse the Fe–O axis and a third that is perpendicular to it, as found in the structure of the iron(II) precursor.^[9] In isomer **B** one ring eclipses the Fe–O axis and two are perpendicular to it, whereas in isomer **C** two rings are perpendicular to the Fe–O axis and the other is coordinated trans to the oxygen atom.

We found ¹H NMR spectroscopy to be a very useful technique to probe the structures of the nonheme oxoiron(IV) complexes, and the spectra of 1 and 2 are shown in Figure 3. The S = 1 iron(iv) centers of 1 and 2 have favorable electronic relaxation properties that give rise to relatively sharp and well-resolved, paramagnetically shifted proton resonances that span 200 ppm. The number of signals observed for 1 is consistent with the presence of mirror symmetry, as established from the solid-state structure. Two sets of pyridine resonances (β , β' , and γ) can be readily identified by a COSY experiment (see Supporting Information). The shift pattern for the protons of the pyridine rings is unique for the low-spin iron(IV) center, with one β proton shifted downfield and the β' proton shifted upfield. In iron(II) and iron(III) pyridine complexes, both β protons are typically shifted downfield with comparable paramagnetic shifts.^[10,11]



Figure 2. The three possible isomers (A–C) of $[Fe^{IV}(O)(R\text{-}TPEN)]^{2+}$ complexes. $R\!=\!Bn$ or Me.

Not surprisingly, the ¹H NMR spectrum of **2** is more complex as a result of the lower symmetry of this complex. Two sets of pyridine β , γ , and β' protons are readily identified from their COSY cross peaks (see Supporting Information) and found at chemical shifts that are comparable to those found for **1**. Their integrations indicate that these peaks account for only two of the three pyridine rings in the complex. Examination of a second COSY spectrum with a narrower spectral width (see Supporting Information) reveals the β , γ , and β' protons of the third pyridine. These protons exhibit smaller paramagnetic shifts and have a distinct shift pattern in which both β and β' peaks are shifted upfield and the peak for the γ proton is shifted downfield. The spectrum



Figure 3. ¹H NMR spectra of **1** (a) and **2** (b, and insets) in CD₃CN. Peaks from pyridine ring protons are assigned based on cross peaks identified in COSY spectra. The left inset shows the expanded region near $\delta = 0$ ppm (0.5×) for **2** and reveals the third set of pyridine ring protons, while the right inset shows the $-30 > \delta > -75$ ppm region (10×) of **2**.

of the corresponding 5-Me-Bn-TPEN complex **4** shows the disappearance of the β'_c proton, thereby leading us to assign the c set of pyridine protons to the unique pyridine on the Bn-TPEN ligand.

The presence of a pyridine ring with a unique shift pattern in 2 suggests that the Bn-TPEN ligand adopts a wrapping mode that corresponds to isomer **A** (Figure 2). The two pyridines that display similar shift patterns to those found in **1** would correspond to the two that are parallel to the Fe–O axis, while the pyridine that lies perpendicular to the Fe–O axis would give rise to the unusual shift pattern. The difference in their paramagnetic shifts can be easily rationalized by the fact that these pyridines must interact differently

with iron d orbitals that have differing amounts of unpaired spin density.

To provide a theoretical foundation upon which to interpret our observations, DFT calculations were carried out to assess the relative energies of the three possible isomers of **2** (Figure 2). Of several models examined, the pure density functional BPW91 model provided an optimized structure for **1** that agreed well with crystallographic data (0.0957 Å root-mean-square deviation over all heavy atoms; see Supporting Information for results using all functionals). Primarily on this basis, BPW91 was chosen for the study of **2**. Table 1 provides Fe–O bond lengths and relative energies for all optimized structures and spin states. The triplet state is

metrical parameters for this com-

plex and shows the expected ligand topology in which all four pyridines are oriented approximately parallel to the Fe=O axis. In the absence of a crystal structure for **2**, NMR spectral data and DFT calculations clearly favor **2A** as the most stable isomer. We thus conclude that pyridine rings aligned parallel to the Fe=O bond contribute significantly to the stability of the oxoir-

on(IV) unit and allow such com-

plexes to be observed at room

Table 1: Relative BPW91 energies (E [kcalmol⁻¹]) for **2A–C** and Fe–ligand bond lengths (Å; for S=1 isomers only).^[a]

	1 ^(b)	2A	2 B	2C	
E (S=1) ^[c]		0.0	5.3	12.5	
$E (S=2)^{[c]}$		16.6	19.0		
Fe-O	1.639	1.640	1.643	1.645	
Fe-N1	2.082 (amine, ax)	2.078 (amine)	2.010 (amine)	2.051 (amine)	
Fe-N2	1.976 (py ∥)	2.022 (py ⊥)	2.040 (py ⊥)	2.058 (py ⊥)	
Fe-N3	1.983 (py)	1.976 (py)	1.976 (py)	2.042 (py ⊥)	
Fe-N4		1.990 (py)	2.002 (py ⊥)	2.104 (py, ax)	
Fe-N5		2.132 (amine, ax)	2.191 (amine, ax)	2.004 (amine)	
$Fe-N_{av}$	2.000	2.040	2.044	2.052	

[a] See Supporting Information for Cartesian coordinates of the geometry-optimized structures of the three isomers **2A–C**. [b] Crystallographic bond lengths for **1** included for comparison. [c] Energy for the S=1 state of isomer **2A** set to zero. py=pyridine, ax=axial.

favored over the pentet state in each of the two lower-energy isomers (the pentet was not converged for isomer **C**), and all further discussion refers only to triplet states.

Of the three isomers of **2**, **A** is predicted to be lowest in energy, with isomers **B** and **C** lying 5.3 and 12.5 kcalmol⁻¹ higher in energy, respectively.^[12] When the iron atom is removed and the relative energies of the frozen ligands are computed at the same level of theory, the relative energies of **A**, **B**, and **C** are found to be 1.0, 0.0, and 2.4 kcalmol⁻¹, respectively. Thus, the relative energies of the iron complexes do not derive from differences in steric energy in the supporting ligand but rather from interactions of the ligand with the Fe=O moiety.

Examination of the data in Table 1 suggests that the metal-ligand bond lengths rationalize the relative stabilities of the three isomers of 2. Equatorial pyridine ligands aligned parallel to the Fe=O axis always have shorter Fe-N bonds than those aligned perpendicular to the Fe=O axis. This shorter distance contributes to the ability of parallel pyridines to stabilize the high-valent iron center through electron donation better than perpendicular pyridines, as judged by second-order perturbation theory in the natural bond orbital (NBO) basis. ^[13,14] The difference in Fe-N bond lengths is easily explained by the greater steric demand of the α hydrogen atoms of the pyridines that lie perpendicular to the Fe=O axis. Thus, among the three isomers of 2, the most stable isomer A has one pyridine ring perpendicular and two rings parallel to the Fe=O axis to give rise to an average bond length of 2.040 Å over all Fe–N bonds. The less-stable isomers, by contrast, both contain two perpendicular equatorial pyridines, with the remaining ring either parallel (B) or trans to the oxo atom (C). These differences give rise to average Fe–N bond lengths of 2.044 and 2.052 Å, respectively. For comparison, all four of the pyridine rings in the N4Py complex 1 are oriented parallel to the Fe=O axis with an average Fe-N bond length of 2.00 Å and thereby it achieves maximum stabilization among the four structures. Not surprisingly, the half-life of 1 is an order of magnitude greater than that of 2.

In summary, we have gained structural insight into novel oxoiron(IV) complexes with pentadentate pentaaza ligands by a combination of X-ray crystallography, NMR spectroscopy, and DFT calculations. The X-ray structure of **1** establishes the

Experimental Section

Complexes 1 and 2 were generated from their respective iron(1) precursors following reported procedures,^[8] while the generation of 4 followed a similar protocol. The synthesis for the precursor to 4, $[(5-Me-Bn-TPEN)Fe^{II}(OSO_2CF_3)](SO_3CF_3)$, is described in the Supporting Information.

temperature.

¹H NMR spectra were recorded on a Varian Inova VI-500 spectrometer at ambient temperature, with reported ¹H NMR chemical shifts (δ [ppm]) referenced to residual solvent peaks. The COSY spectrum for **1** was collected using 256 points in t_1 with a spectral width of 54.3 kHz and a delay of 30 ms. The COSY spectra for **2** were collected using 256 points in t_1 with spectral widths of 47.8 and 19.7 kHz and a delay of 30 ms.

X-ray crystal structure data for 1: Blue needles were isolated upon layering pentane on a solution of 1 in acetonitrile: $C_{27}H_{27}Cl_2FeN_7O_9$, monoclinic, space group Cm, a = 11.955(4), b =17.954(5), c = 7.084(2) Å, $\beta = 93.708(5)^{\circ}$, V = 1517.3(8) Å³, Z = 2, $\rho_{\text{calcd}} = 1.577 \text{ g cm}^{-3}$, crystal dimensions: $0.32 \times 0.12 \times 0.04 \text{ mm}^3$; Bruker CCD diffractometer; $Mo_{K\alpha}$ radiation, 173(2) K; $2\theta_{max} =$ 50.1°, 5606 reflections, 2669 independent ($R_{int} = 0.0454$), direct methods; multiscan absorption correction ($\mu = 0.739 \text{ mm}^{-1}$); refinement (on F^2) with SHELXTL-Plus (version 5.10), 301 parameters, 126 restraints, $R_1 = 0.0499$ ($I > 2\sigma$) and wR_2 (all data) = 0.1178, GOF = 1.046, max/min residual electron density: 0.435/-0.211 e Å⁻³. CCDC 261401 (1) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/ cif. See Supporting Information for additional experimental details.

Computational Methods: The molecular geometry of $[Fe(O)-(N4Py)]^{2+}$ (S = 1) was optimized at the unrestricted BLYP,^[15,16] BPW91,^[16,17] BP86,^[15,18,19] BP86-VWN5,^[15,19,20] B3LYP,^[15,16,19] B3PW91,^[15,17] B3P86,^[15,19,20] and BHANDH^[15] levels using the LACVP*^[21-23] effective core potential on iron and the 6-31G**^[24-29] basis set on all other atoms. The BPW91 model was found to provide good agreement with the known crystal structure and was chosen on this basis for modeling Fe(Me-TPEN) (in Me-TPEN, the benzyl group of Bn-TPEN is replaced by a methyl group). Three conformers of Fe(Me-TPEN) were optimized at this level for the S = 1 spin state, and in the two lowest energy cases for the S = 2 spin state. All structures were verified as minima by computation of analytical vibrational frequencies. Calculations were performed using Jaguar 5.0^[30] and Jaguar NBO Version 5.0.^[31]

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