Structure and Mössbauer Spectrum of a (μ-1,2-Peroxo)bis(μ-carboxylato)diiron(III) Model for the Peroxo Intermediate in the Methane Monooxygenase Hydroxylase Reaction Cycle

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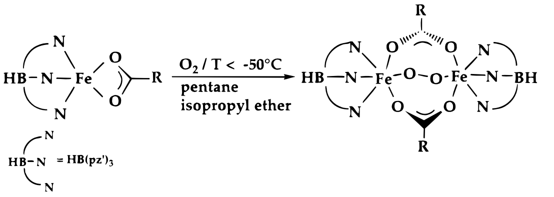
Received February 12, 1996

The ability of bacteria to use methane as their sole source of carbon and energy has fascinated chemists interested in C−H activation.[1,2] The key catalytic component in soluble methane monooxygenase (MMO) systems is a 251 kDa hydroxylase enzyme containing two noninteracting carboxylate-bridged dinuclear non-heme iron centers.[3−5] Recently, freeze−quench kinetic studies of the reaction with dioxygen of the reduced hydroxylase (H_{red}) component of MMO from *Methylococcus capsulatus* (Bath) afforded optical, Raman, and Mössbauer spectra which were tentatively assigned to an antiferromagnetically coupled (μ-peroxo)diiron(III) intermediate designated H_{peroxo}.[6,7] The optical absorption spectral band at 600−650 nm and the $\nu_{\text{O−O}}$ stretching frequency of 905 cm^{-1} supported this assignment, but the isomer shift in the Mössbauer spectrum (δ, 0.66 mm s^{-1}) was outside the range of those previously reported for diiron(III) peroxo complexes.

Although unstable peroxo-bridged diiron(III) complexes had been spectroscopically identified, no X-ray structural determination had been published at the inception of this work,[8,9] and none had the specific Mössbauer parameters of H_{peroxo}. We therefore sought to characterize crystallographically a small molecule analog of the putative peroxo intermediate and to obtain its Mössbauer spectrum for comparison to that of H_{peroxo}. One likely candidate was the blue-green species formed in the reaction of [Fe{HB(pz′)$_3$}(O$_2$CR)], pz′ = 3,5-bis(isopropyl)-pyrazolyl and R = Ph, with dioxygen at low temperature.[10] After extensive trials with different R groups (R = Ph (**1a**), CH$_2$Ph (**2a**), *p*-tol (**3a**), 4-biphenyl (**4a**), and 2-naphthyl (**5a**)) and crystallization conditions, and with the power of a CCD-detector-based X-ray diffractometer, we finally succeeded in characterizing one such complex, [Fe$_2$(μ-1,2-O$_2$)(μ-O$_2$CCH$_2$Ph)$_2$-{HB(pz′)$_3$}$_2$], **2b**, by crystallographic chemical analysis (CCA). The structure and spectroscopic, including frozen solution Mössbauer, properties of **2b** and its precursor [Fe{HB(pz′)$_3$}-(O$_2$CCH$_2$Ph)], **2a**, form the basis for the present communication.

The mononuclear iron(II) carboxylate complex [Fe{HB-(pz′)$_3$}(O$_2$CCH$_2$Ph)], **2a**, was prepared by a method analogous to that described for **1a**[10] except that [Fe{HB(pz′)$_3$}Br] was used as the starting material. The complex was characterized by IR spectroscopy, elemental analysis (see the supporting information), and X-ray crystallography.[11] The peroxo complex [Fe$_2$(μ-O$_2$)(μ-O$_2$CCH$_2$Ph)$_2${HB(pz′)$_3$}$_2$], **2b**, was synthesized by allowing **2a** to react with anhydrous dioxygen at temperatures below −50 °C (eq 1). Crystals were grown at −80 °C by the vapor diffusion method. After numerous unsuccessful attempts with other peroxo complexes [Fe$_2$(μ-O$_2$){(μ-O$_2$CR)}$_2${HB-(pz′)$_3$}$_2$] (R = phenyl (**1b**), *p*-tol (**3b**), 4-biphenyl (**4b**), and 2-naphthyl (**5b**)), only peroxo complex **2b** afforded crystals suitable for CCA.



(1)

The structure of **2b** is presented with selected metrical details in Figure 1.[12] The crystal lattice contains an asymmetric unit comprising two independent molecules of **2b** with very similar geometries and several solvent molecules. Two iron atoms are linked by two bridging phenylacetate ligands and a bridging peroxo ligand in a structure which differs from the one proposed for [Fe$_2$(μ-O$_2$){(μ-O$_2$CPh)}$_2${HB(pz′)$_3$}$_2$] (**1b**).[10] It was postulated that the two iron atoms are bridged only by the peroxo ligand and that the two carboxylate ligands chelate to the different iron centers. The average Fe···Fe separation is 4.004-(4) Å, shorter than the value of 4.3 Å estimated from EXAFS data for [Fe$_2$(μ-O$_2$)(μ-O$_2$CPh)$_2${HB(pz′)$_3$}$_2$].[10] The peroxo unit coordinates to the two iron atoms in a μ-1,2-bridging mode with an average Fe−O−O−Fe dihedral angle of 52.9°. This feature is interesting and may account for spectroscopic differences between complex **2b** and other (μ-1,2-peroxo)diiron(III) complexes. In these latter species, the Fe−O−O−Fe units are constrained to near planarity by the presence of an additional single atom bridge and have dihedral angles approaching 0°.[8,9] The peroxo ligand is effectively shielded by the isopropyl side chains of the pyrazolylborate ligands (Figure S1). The average O−O distance, 1.408(9) Å, and Fe−O(peroxo) bond length of 1.885(12) Å are typical of those in other μ-1,2-peroxo structures.[8,9] The two carboxylate ligands form symmetric bridges between the iron centers with an average Fe−O distance of 2.049(11) Å.

The spectroscopic properties of **1b**, **2b**, and the H_{peroxo} intermediate of MMO are summarized in Table 1, and UV−visible, Raman, and Mössbauer spectral traces of **2b** are provided as supporting information. Complex **2b** exhibits a broad absorption band at 694 nm with a molar coefficient of 2650 M^{-1} cm^{-1}, assigned as a LMCT transition in the analogous

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(11) X-ray data for [Fe{HB(pz′)$_3$}(O$_2$CCH$_2$Ph)]·C$_5$H$_{12}$: monoclinic, $P2_1/c$, a = 17.476(7) Å, b = 14.939(6) Å, c = 16.191(7) Å, β = 92.54(3)°, V = 4,223(3) Å^3 at −150 °C with Z = 4; $R1$ = 0.102 ($I > 2\sigma(I)$). The coordination geometry of iron in this structure is similar to that found for **1a** (ref 10).

(12) The compound 2[Fe$_2$(μ-1,2-O$_2$)(μ-O$_2$CCH$_2$Ph)$_2${HB(pz′)$_3$}$_2$]·0.5CH$_2$-Cl$_2$·0.5(i-Pr$_2$O)·2.5C$_5$H$_{12}$ crystallized in space group $P2_1/n$, a = 17.222(4) Å, b = 24.206(4) Å, c = 45.449(10) Å, β = 96.198(11)°, V = 18 836(7) Å^3 at −150 °C with Z = 4. Data were collected on a Siemens SMART diffractometer equipped with a CCD detector and Mo Kα radiation. With the use of 23 205 reflections, the structure was refined to a conventional R value ($I > 2\sigma(I)$) of 0.142. This high residual reflects poor crystal quality (>100 crystals were examined and 4 complete data sets were collected), a large unit cell (1801 parameters), high solvent content, and solvent disorder. Details are available as supporting information.

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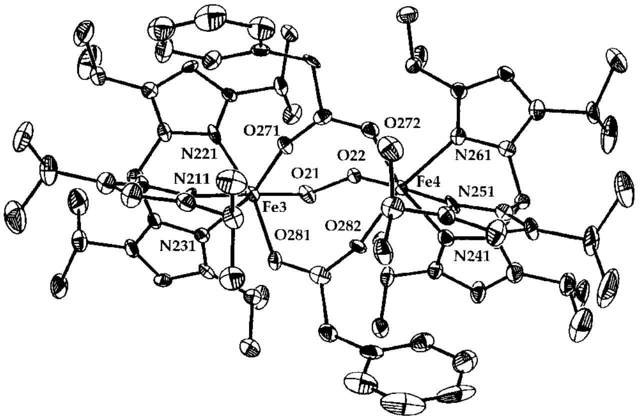

Figure 1. ORTEP diagram of one of the two independent molecules in the asymmetric unit, $[Fe_2(\mu\text{-}O_2)(\mu\text{-}O_2CCH_2Ph)_2\{HB(pz')_3\}_2]$ (**2b**), showing the 50% probability thermal ellipsoids for all non-hydrogen atoms. Selected interatomic distances (Å) and angles (deg) are as follows: Molecule 1 (see Figure S1), Fe1−O11, 1.905(6); Fe2−O12, 1.876(6); Fe1−O171, 2.037(7); Fe2−O172, 2.058(6); Fe1−O181, 2.050(7); Fe2−O182, 2.050(7); Fe1−N111, 2.192(8); Fe1−N121, 2.222(8); Fe1−N131, 2.143(8); Fe2−N141, 2.171(8); Fe2−N151, 2.159(7); Fe2−N161, 2.205(8); O11−O12, 1.409(9); Fe1···Fe2, 4.000(4); Fe1−O11−O12, 128.3(5); Fe2−O12−O11, 129.5(5), $Fe_1-O_{11}-O_{12}-Fe_2$ dihedral, 52.3°. Molecule 2 (depicted), Fe3−O21, 1.881(6); Fe4−O22, 1.877(6); Fe3−O271, 2.028(6); Fe4−O272, 2.067(6); Fe3−O281, 2.052(6); Fe4−O282, 2.046(6); Fe3−N211, 2.218(8); Fe3−N221, 2.182(8); Fe3−N231, 2.163(8); Fe4−N241, 2.167(8); Fe4−N251, 2.218(8); Fe4−N261, 2.177(8); O21−O22, 1.406(8); Fe3···Fe4, 4.007(4); Fe3−O21−O22, 128.9(5); Fe4−O22−O21, 129.7(5), $Fe_3-O_{21}-O_{22}-Fe_4$ dihedral, 53.5°.

Table 1. Selected Spectroscopic Properties for **1b**, **2b**, and the H_{peroxo} Intermediate of MMO

		1b[a]	**2b**	H_{peroxo}[b]
optical	λ_{max} (ϵ) nm (cm^{-1} M^{-1})	682 (3450)	694 (2650)	≈600−650
Mössbauer	δ (mm s^{-1})		0.66	0.66
	ΔE_Q (mm s^{-1})		1.40	1.51
	$\Gamma_{1/2}$ (mm s^{-1})		0.15	0.27
Raman	ν(O−O) (cm^{-1})	876	888	905
	ν(Fe−O) (cm^{-1})	418	415	

[a] Reference 10. [b] References 6 and 7.

benzoate complex **1b**.[10] The slight differences in λ_{max} and ϵ values between **1b** and **2b** probably arise from the different electron-donating abilities of benzoate and phenylacetate. Resonance Raman spectra of **2b** were measured in toluene solution at −78 °C with excitation at 647 nm. Samples prepared with $^{16}O_2$ gave rise to ν(O−O) and ν(Fe−O) bands at 888 and 415 cm^{-1}, respectively, which shifted to 842 and 404 cm^{-1} for material generated with $^{18}O_2$. The magnitudes of the frequency shifts are in good agreement with the theoretical values of 50 and 10 cm^{-1}. Corresponding Raman bands occur at 876 and 418 cm^{-1} for the $^{16}O_2$ derivative of the benzoate complex **1b** and at 827 and 409 cm^{-1} for the $^{18}O_2$ derivative.[10] A 4.2 K Mössbauer spectrum of a frozen sample of **2b** in toluene displays a sharp ($\Gamma_{1/2} = 0.15$ mm s^{-1}), symmetric quadrupole doublet with $\delta = 0.66$ mm s^{-1} and $\Delta E_Q = 1.40$ mm s^{-1}. These parameters are very unusual and, until recently, had never been reported for carboxylate-bridged diiron complexes. In particular, the isomer shift is significantly greater than the 0.45−0.55 mm s^{-1} range typically observed for carboxylate-bridged diiron(III) clusters.[13−15] The isomer shift of **2b** is identical, and the quadrupole splitting similar, to the corresponding values recently observed for the H_{peroxo} intermediate of MMO ($\delta = 0.66$ mm s^{-1} and $\Delta E_Q = 1.51$ mm s^{-1}),[7] strongly supporting its structural assignment as a diiron(III) peroxo species. Isomer shifts of 0.58 and 0.74 mm s^{-1} and $\Delta E_Q = 0.74$ and 1.70 mm s^{-1}, respectively, were recently reported for a solid sample of $[Fe_2(\mu\text{-}1,2\text{-}O_2)(\mu\text{-}O_2CPh)(Ph\text{-}bimp)]^{2+}$, Ph-bimp = 2,6-bis[bis{2-(1-methyl-4,5-diphenylimidazolyl)methyl}aminomethyl]-4-methylphenolate, a complex having asymmetric Fe−O(peroxide) bonds.[9] These values do not match those of the protein as well as do the parameters of **2b**.

In conclusion, owing to the availability of a CCD detector diffractometer it has been possible to characterize by CCA a representative member of the previously reported (μ-peroxo)diiron(III) family, $[Fe_2(\mu\text{-}1,2\text{-}O_2)(\mu\text{-}O_2CCH_2Ph)_2\{HB(pz')_3\}_2]$, **2b**.[10] The two iron atoms are linked by two bridging phenylacetate ligands and a peroxo ligand coordinated in a *cis*-μ-η^1:η^1 fashion. Mössbauer study shows that the sharp, single isomer shift of the diiron peroxo complex is almost the same as that of the peroxo intermediate of MMO and may be of more general relevance to intermediates in the reactions of non-heme iron proteins and small molecule mimics with dioxygen.[1]

Acknowledgment. This work is dedicated to the memory of Nobu Kitajima and was supported by Grant GM 32134 from the National Institute of General Medical Sciences. K.K. is grateful to the Yonam Foundation and to the Korea Science and Engineering Foundation for support of his stay at MIT. We thank Drs. R. J. Lachicotte and M. J. Scott for help with the crystal structure determination, Dr. G. C. Papaefthymiou for obtaining and fitting the Mössbauer spectrum, Ms. J. W. Yun for assistance in recording the Raman spectra, and Professors L. Que, Jr., and M. Suzuki for access to unpublished results.

Supporting Information Available: Experimental details of the crystal structure determination of $2[Fe_2(\mu\text{-}O_2)(\mu\text{-}O_2CCH_2Ph)_2\{HB(pz')_3\}_2]\cdot 2.5C_5H_{12}\cdot 0.5C_6H_{14}O\cdot 0.5CH_2Cl_2$, **2b**, including an ORTEP diagram of an alternative view (Figure S1) as well as tables of atomic parameters and molecular geometry (Tables S1−S5), and UV−visible, Raman, and Mössbauer spectral traces (Figures S2−S4) (56 pages). Ordering information is given on any current masthead page.

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