

Carboxylate-Bridged Diiron(II) Complexes, Including a New Model for Reduced Methane Monooxygenase Hydroxylase and the R2 Protein of Ribonucleotide Reductase

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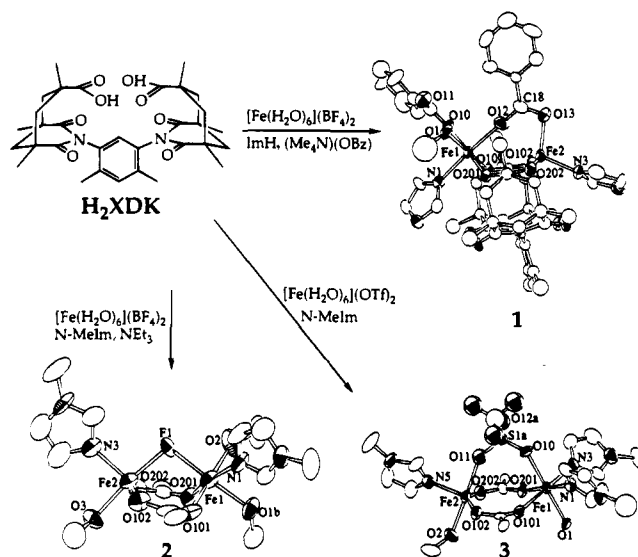
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Carboxylate-bridged diiron centers comprise the active sites of non-heme iron proteins including hemerythrin (Hr),¹ purple acid phosphatase,² the R2 protein of ribonucleotide reductase,³ and soluble methane monooxygenase hydroxylase (sMMOH).⁴ Crystallographic studies of the reduced form of the R2 protein show two iron atoms at a distance of 3.8 Å bridged by two carboxylate groups. The oxygen-rich coordination sphere at each of the two pentacoordinate ferrous ions is completed by one histidine residue and one additional bidentate carboxylate group.^{3c} Preliminary data from the X-ray structure of reduced sMMOH reveal two ferrous ions, bridged by two glutamate carboxylate groups, one having a bidentate *syn-syn* coordination mode and the other being monodentate bridging as well as chelating to one of the metal ions. The iron coordination spheres are oxygen-rich, with only two histidine residues as terminal ligands.^{4b}

A variety of multidentate ligands have been used to synthesize diiron(III) carboxylate model compounds, which have afforded considerable insight into the structural and physical properties of these proteins.⁵ To mimic the dioxygen reactivity found in the biological systems, however, diiron(II) model complexes are needed. The preparation of these complexes is more challenging, and structurally characterized diiron(II) carboxylate compounds are correspondingly fewer in number.⁶ To reduce the kinetic lability of the ferrous centers in these complexes, which favors formation of undesired oligomers, multidentate N-donor ligands have been used, often providing a coordination environment different from that found in the sMMOH and the R2 protein active sites. We report here a general route to the

Scheme 1



synthesis of diiron(II) model compounds bridged by the dicarboxylate XDK ($H_2XDK = m$ -xylenediamine bis(Kemp's triacid)imide), a ligand that has proved to be very useful for the preparation of homo- and heterodimetallic complexes with a variety of metal ions.^{6i,7} In particular, we describe the preparation and X-ray structural characterization of $[Fe_2(\mu-OBz)(XDK)(ImH)_2(OBz)(MeOH)]$ (**1**),⁸ a diiron(II) complex with an O-rich coordination sphere that represents a reasonable model for the reduced forms of the diiron cores in sMMOH and the R2 protein.

The synthetic route to the bis(carboxylato)-bridged complexes is summarized in Scheme 1, where, for clarity, a portion of the XDK ligand is deleted for **2** and **3**. The tris(carboxylato)-bridged complex $[Fe_2(\mu-OBz)(XDK)(ImH)_2(OBz)(MeOH)]$ (**1**) was assembled under anaerobic conditions by reacting a 2:1:2:2:3 ratio of $[Fe(H_2O)_6](BF_4)_2$, H_2XDK , Et_3N , imidazole, and $(Me_4N)(OBz)$ in a $MeOH/CH_2Cl_2$ mixture. The X-ray structure of **1** reveals 4- and 6-coordinate Fe(II) ions at a distance of 3.609(4) Å, bridged by the two carboxylate groups of XDK and further by a benzoate anion (Figure 1). A N-donor of an imidazole completes the coordination sphere of the unusual 4-coordinate ferrous ion, Fe(2). The terminal sites of the octahedrally coordinated Fe(1) ion are filled by a N-donor of an imidazole, a hydroxyl oxygen atom of methanol, and a monodentate benzoate hydrogen bonded to the MeOH ligand ($O(1) \cdots O(11)$, 2.50(2) Å). The average Fe–O and Fe–N bond lengths for the tetrahedral Fe(2) center are significantly shorter than for the octahedral Fe(1) site (Fe(1)– O_{av} , 2.13(5) Å; Fe(1)–N(1), 2.13(1) Å; Fe(2)– O_{av} , 2.00(4) Å; Fe(2)–N(3), 2.05(1) Å). The geometry around Fe(2) is distorted tetrahedral, with the largest deviation from idealized angles caused by a weak interaction between Fe(2) and O(12), which opens the $O(102)–Fe(2)–O(202)$ angle to 138.3(5)°. The $Fe(2) \cdots O(12)$ distance is 2.52(1) Å. Compound **1** represents the first example of a carboxylate-rich diiron(II) complex with only monodentate N-donor ligands and has the same composition, four carboxylates, two imidazoles, and a solvent molecule, as the active site of reduced sMMOH.

The bridging benzoate ligand has a very unusual coordination mode, with a nearly linear $Fe(1)–O(12)–C(18)$ bond angle of

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(8) Abbreviations used: ImH, imidazole; 6-MeQ, 6-methylquinoline; N-Melm, N-methylimidazole; OTf, O_3SCF_3 .

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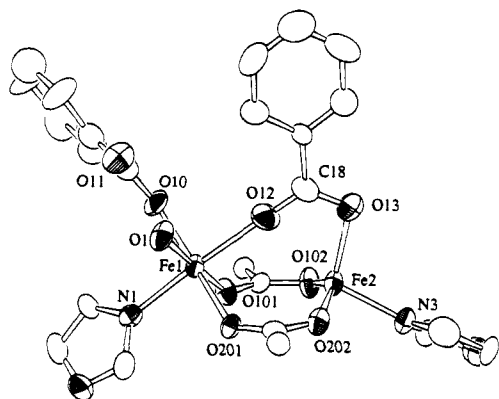


Figure 1. ORTEP plots showing 50% probability thermal ellipsoids of $[\text{Fe}_2(\mu\text{-OBz})(\text{XDK})(\text{ImH})_2(\text{OBz})(\text{MeOH})]$ (**1**). For clarity, hydrogen atoms, the carbon atom of the coordinated MeOH, all atoms of the XDK ligand, except for the carboxylate group and the α -carbon atoms have been omitted. Selected interatomic distances (\AA) and angles (deg) for **1**: $\text{Fe}(1) \cdots \text{Fe}(2)$, 3.609(4); $\text{Fe}(1)\text{-O}(1)$, 2.12(1); $\text{Fe}(1)\text{-O}(10)$, 2.10(1); $\text{Fe}(1)\text{-O}(12)$, 2.20(1); $\text{Fe}(1)\text{-O}(101)$, 2.06(1); $\text{Fe}(1)\text{-O}(201)$, 2.15(1); $\text{Fe}(1)\text{-N}(1)$, 2.13(1); $\text{O}(1) \cdots \text{O}(11)$, 2.50(2); $\text{Fe}(2) \cdots \text{O}(12)$, 2.52(1); $\text{Fe}(2)\text{-O}(13)$, 2.04(1); $\text{Fe}(2)\text{-O}(102)$, 1.97(1); $\text{Fe}(2)\text{-O}(202)$, 1.98(1); $\text{Fe}(2)\text{-N}(3)$, 2.05(1); $\text{O}(12)\text{-C}(18)$, 1.24(2); $\text{O}(13)\text{-C}(18)$, 1.26(2); $\text{O}(12)\text{-Fe}(1)\text{-O}(10)$, 90.4(5); $\text{O}(12)\text{-Fe}(1)\text{-N}(1)$, 173.3(5); $\text{O}(101)\text{-Fe}(1)\text{-O}(201)$, 95.8(4); $\text{O}(13)\text{-Fe}(2)\text{-N}(3)$, 107.1(5); $\text{O}(102)\text{-Fe}(2)\text{-O}(202)$, 138.2(5); $\text{O}(202)\text{-Fe}(2)\text{-N}(3)$, 95.7(5); $\text{O}(102)\text{-Fe}(2)\text{-N}(3)$, 95.4(5); $\text{Fe}(1)\text{-O}(12)\text{-C}(18)$, 178(1); $\text{O}(12)\text{-C}(18)\text{-O}(13)$, 121(2); $\text{C}(18)\text{-O}(13)\text{-Fe}(2)$, 102(1).

$178(1)^\circ$ (Figure 1). The Fe(1) atom seems not to be bound in the traditional manner to either the *anti* or the *syn* lone pairs of O(12). Instead, the bridging carboxylate ligand may be regarded as in transition between the *syn-anti* and *syn-syn* coordination modes. Carboxylate shifts of this kind between binding modes were postulated to be involved in reactions that occur in metalloprotein active sites containing Glu or Asp ligands⁹ and are now known for both the R2 protein³ and sMMOH.⁴ Transitions from the monodentate to the bidentate *syn-syn* bridging mode might proceed via a *syn-anti* rearrangement, which in small molecule model compounds increases the distance between the two involved metal centers.^{6f} The relatively short $\text{Fe} \cdots \text{Fe}$ distance in **1**, 3.609(4) \AA , comparable to that found in monodentate-bridged diiron(II) compounds,^{6c,10} reveals that the dicarboxylate ligand XDK allows this transition to occur without a significant increase in $\text{Fe} \cdots \text{Fe}$ distance. A very similar geometry occurs in the linear trinuclear complex $[\text{CaZn}_2(\text{crot})_6(6\text{-MeQ})_2]$, where a bridging crotonate ligand links a tetrahedrally coordinated Zn(II) to the central octahedral Ca(II) ion, the Ca-O-C angle being $170.0(2)^\circ$.¹¹

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The dicarboxylate ligand XDK also facilitates preparation of a variety of other dinuclear ferrous compounds, which seem to require a third bridging ligand to stabilize the $\{\text{Fe}_2(\text{XDK})\}^{2+}$ core. Complexes $[\text{Fe}_2(\mu\text{-F})(\text{XDK})(\text{N-MeIm})_2(\text{MeOH})_3](\text{BF}_4)$ (**2**), $[\text{Fe}_2(\mu\text{-OTf})(\text{XDK})(\text{N-MeIm})_3(\text{MeOH})(\text{H}_2\text{O})](\text{OTf})$ (**3**), and $[\text{Fe}_2(\mu\text{-Cl})(\text{XDK})(\text{N-MeIm})_2(\text{MeOH})_3](\text{BF}_4)$ (**4**) were readily assembled in the presence of fluoride, triflate, or chloride ions, respectively, by following an analogous route (Scheme 1). The X-ray structures of **2**, **3**, and **4** reveal a comparably asymmetrical arrangement of the ligands, with trigonal bipyramidal 5-coordinate and octahedral 6-coordinate Fe atoms bridged by the two carboxylates of XDK and by a third ligand F^- , triflate, and Cl^- , respectively. The $\text{Fe} \cdots \text{Fe}$ distance varies only slightly for the halide-bridged complexes **2** and **4** (**2**, $\text{Fe}(1) \cdots \text{Fe}(2)$, 3.398(2) \AA ; **4**, $\text{Fe}(1) \cdots \text{Fe}(2)$, 3.552(2) \AA), as expected from covalent radii changes, but is significantly longer in the triflate-bridged compound **3** ($\text{Fe}(1) \cdots \text{Fe}(2)$, 4.120(3) \AA). Attempts to substitute the chloride bridge by extracting it with a Ti^+ salt resulted, in the case of $\text{Ti}(\text{OAc})$, in the formation of a mixture of the corresponding acetate-bridged complex $[\text{Fe}_2(\mu\text{-OAc})(\text{XDK})(\text{N-MeIm})_2(\text{MeOH})_3](\text{BF}_4)$ and mononuclear $[\text{Fe}(\text{HXDK})_2(\text{MeOH})_2]$, further indicating the propensity for a third bridging ligand to link the diiron(II) $\{\text{Fe}_2(\text{XDK})\}^{2+}$ core.

In summary, we have discovered a versatile route to bis(μ -carboxylato)diiron(II) complexes with only O- and monodentate N-donors having a variety of additional ligands in the bridging position, allowing us to prepare a model for the reduced diiron centers in the R2 protein and sMMOH. Preliminary magnetic measurements indicate that the two iron centers are weakly antiferromagnetically coupled ($|J| \leq 5 \text{ cm}^{-1}$) in all of the complexes, regardless of the nature of the bridging ligand. The reactivity of these compounds with dioxygen and other reagents is currently under investigation.

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Supplementary Material Available: Experimental details on the preparation and characterization of **1-4**, including analytical and crystallographic data, full ORTEP plots of **2-4**, selected bond lengths and angles, and tables of positional and thermal parameters for **1-4** (18 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, can be ordered from the ACS, and can be downloaded from the Internet; see any current masthead page for ordering information and Internet access instructions.

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