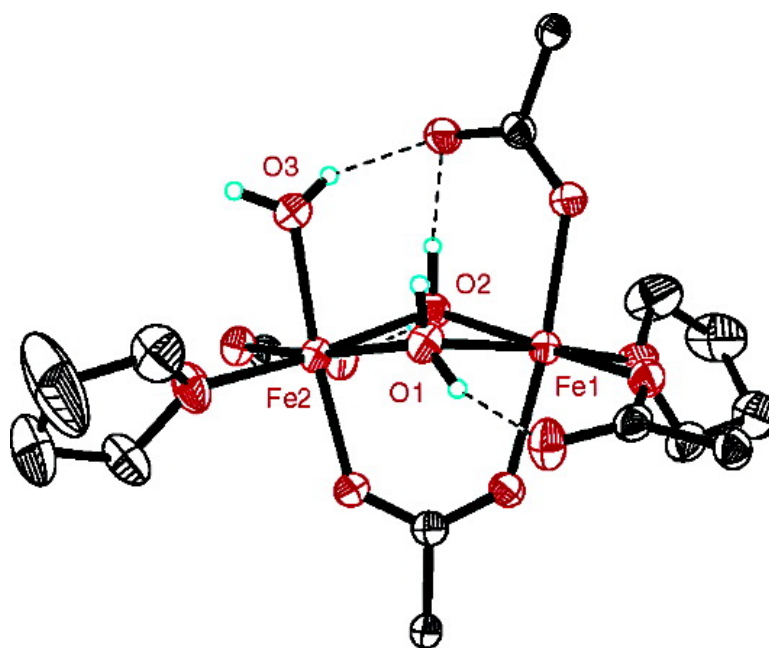


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## Water-Dependent Reactions of Diiron(II) Carboxylate Complexes

Sungho Yoon and Stephen J. Lippard\*

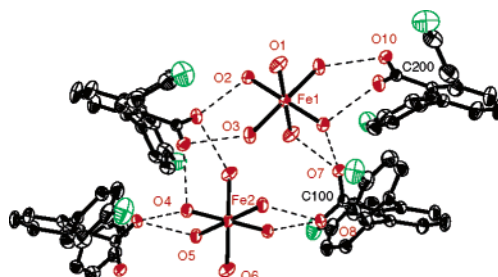
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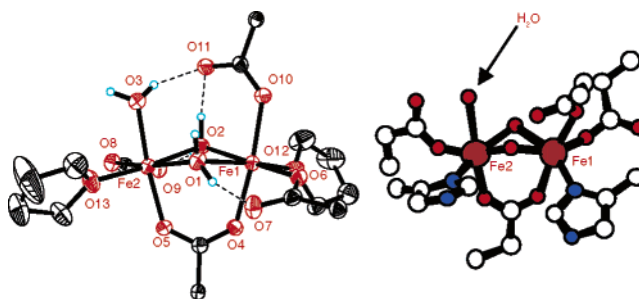
Carboxylate-bridged diiron(II) cores, housed in four-helix bundles, occur frequently at the active sites of dioxygen-dependent non-heme diiron enzymes.<sup>1–5</sup> The R2 subunit of ribonucleotide reductase (RNR-R2),<sup>6</sup>  $\Delta$ -9-desaturase ( $\Delta$ -9D),<sup>7</sup> toluene monooxygenase (ToMO),<sup>8</sup> and the hydroxylase component of soluble methane monooxygenase (sMMOH)<sup>9,10</sup> are important members of this metalloprotein family. Much effort has been devoted to reproducing the structures and functions of the active sites in these enzymes by synthetic model complexes.<sup>11–16</sup> Although it has been proposed that water in the coordination sphere is a key participant in the oxygenation chemistry of these enzymes,<sup>5,17,18</sup> few of the models address the effects of water on the reactions of carboxylate-rich diiron(II) complexes.<sup>19,20</sup> Recently, we reported the designed synthesis of water-containing diiron(II) complexes as our initial effort to address this issue through model chemistry.<sup>21</sup> Here we describe the isolation and characterization of novel iron(II) complexes with varying numbers of ligated water molecules, indicating the existence of water-dependent structures involving the carboxylate-bridged diiron(II) core.

The dissolution of  $[\text{Fe}_2(\mu\text{-O}_2\text{CAr}^{4\text{F-Ph}})_2(\text{O}_2\text{CAr}^{4\text{F-Ph}})_2(\text{THF})_2]$ ,<sup>11</sup> where  $\text{-O}_2\text{CAr}^{4\text{F-Ph}}$  is 2,6-di-(*p*-fluorophenyl)benzoate,<sup>22</sup> in THF containing 35 equiv of water, followed by pentane diffusion into the solution, results in long colorless needles of  $[\text{Fe}(\text{H}_2\text{O})_6](\text{O}_2\text{CAr}^{4\text{F-Ph}})_2 \cdot 2\text{THF}$  (**1**), the structure of which is depicted in Figure 1. Two octahedral hexaaquairon(II) units are housed in the unit cell, with Fe–O bond lengths ranging from 2.104(2) to 2.167(2) Å. The charge of the hexaaquairon(II) cation is balanced by two carboxylate groups, and there are also two THF molecules in the asymmetric unit. The average O···O distance between the carboxylate and coordinated water oxygen atoms is 2.73(6) Å, indicating the presence of hydrogen bonding interactions. All 12 hydrogen atoms in the six water molecules are involved in a hydrogen bonding network along a one-dimensional iron(II) channel (Figures S1 and S2, Supporting Information). Two modes of orientation, parallel and perpendicular to the direction of the channel, repeat along this dimension. The colorless needles quickly turn yellow when removed from solution. This instability precluded further physical characterization of **1**.

Colorless block crystals of  $[\text{Fe}_2(\mu\text{-OH}_2)_2(\mu\text{-O}_2\text{CAr}^{4\text{F-Ph}})(\text{O}_2\text{CAr}^{4\text{F-Ph}})_3(\text{THF})_2(\text{OH}_2)]$  (**2**) form in THF solutions of  $[\text{Fe}_2(\mu\text{-O}_2\text{CAr}^{4\text{F-Ph}})_2(\text{O}_2\text{CAr}^{4\text{F-Ph}})_2(\text{THF})_2]$ <sup>11</sup> containing 17 equiv of water, following vapor diffusion of pentane into the solution. Two iron(II) atoms having pseudo-octahedral coordination geometry are bridged by one carboxylate and two water molecules in **2** (Figure 2). The  $\{\text{Fe}_2(\mu\text{-OH}_2)_2\}^{4+}$  unit is bent up and away from the bridging carboxylate, and the Fe···Fe distance is 3.288(1) Å. Although this diiron(II) core has not been previously reported in structures of either small molecules or metalloproteins, a very similar motif occurs in the  $\{\text{Fe}_2(\mu\text{-OH})_2(\mu\text{-O}_2\text{CR})(\text{OH}_2)\}^{3+}$  cores of the enzymes in their diiron(III) oxidation states.<sup>10</sup> Each iron(II) center contains one terminal carboxylate, which forms a strong hydrogen bond with the bridging water molecule. A bridging water is also hydrogen-



**Figure 1.** ORTEP diagram of  $[\text{Fe}(\text{H}_2\text{O})_6](\text{O}_2\text{CAr}^{4\text{F-Ph}})_2 \cdot 2\text{THF}$  (**1**), showing 50% probability thermal ellipsoids for all non-hydrogen atoms. The THF molecules are omitted for clarity. Selected interatomic distances (Å): Fe1–O1, 2.1158(14); Fe1–O2, 2.1279(17); Fe1–O3, 2.1532(15); Fe2–O4, 2.1670(16); Fe2–O5, 2.1246(15); Fe2–O6, 2.1039(18); C100–O7, 1.248(2); C100–O8, 1.253(2); C200–O9, 1.255(2); C200–O10, 1.258(2).

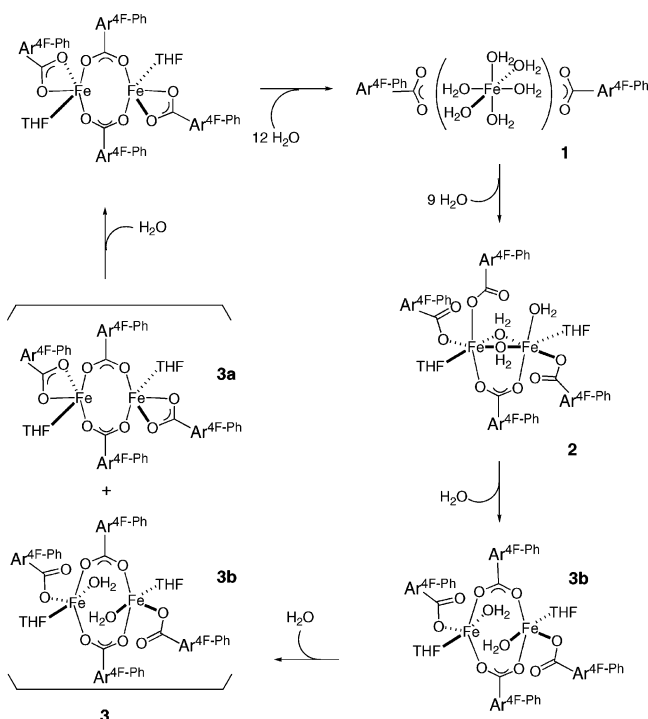


**Figure 2.** ORTEP diagrams of  $[\text{Fe}_2(\mu\text{-OH}_2)_2(\mu\text{-O}_2\text{CAr}^{4\text{F-Ph}})(\text{O}_2\text{CAr}^{4\text{F-Ph}})_3(\text{THF})_2(\text{OH}_2)]$  (**2**) showing 50% probability thermal ellipsoids for all non-hydrogen atoms. The aromatic rings of  $\text{Ar}^{4\text{F-Ph}}\text{CO}_2^-$  ligands and hydrogen atoms in THF molecules are omitted for clarity. Selected interatomic distances (Å) and angles (deg): Fe1–O1, 2.293(2); Fe1–O2, 2.152(2); Fe2–O1, 2.230(2); Fe2–O2, 2.232(2); Fe1–O1–Fe2, 93.27(8); Fe1–O2–Fe2, 97.16(8); O1–Fe1–O2, 81.60(8); O1–Fe2–O2, 81.31(8); Fe2–O3, 2.115(2); O1···O7, 2.549(3); O2···O9, 2.584(3); O2···O11, 2.621(3); O3···O11, 2.719(3); Right: The structure of the diiron(III) core in the  $\text{MMOH}_{\text{ox}}$  resting state.<sup>10</sup>

bonded to the apical carboxylate on Fe1 at an O···O distance of 2.621(3) Å. The apical carboxylate further hydrogen bonds to the terminal water molecule on Fe1 (Figure 2). These interactions stabilize the  $\{\text{Fe}_2(\mu\text{-OH}_2)_2(\mu\text{-O}_2\text{CR})\}^{3+}$  core fragment in **2**.

The zero-field Mössbauer spectrum of **2** at 4.2 K has parameters  $\delta = 1.35(2)$  mm s<sup>–1</sup>,  $E_Q = 3.26(2)$  mm s<sup>–1</sup>, and  $\Gamma = 0.25(2)$  mm s<sup>–1</sup>, indicating that the two different iron sites are indistinguishable under Mössbauer conditions (Figure S3). The isomer shifts are comparable to those of other high-spin iron(II) complexes.<sup>1</sup> Multifield, temperature-dependent magnetic susceptibility measurements<sup>23</sup> of powdered solid samples of **2** were made to address the exchange coupling interaction between the two high-spin iron(II) sites connected by two single atom bridges (Figure S4). The effective magnetic moment ( $\mu_{\text{eff}}$ ) of **2** at 1 T steadily decreases from 7.2  $\mu_B$  at 300 K to 6.6  $\mu_B$  at 2 K. Although this decrease in moment may suggest weak exchange coupling between the two high-spin iron(II) centers of the triply bridged dimer, inclusion of zero field splitting terms revealed otherwise. Excellent fits were obtained with

Scheme 1



$J = 0.02 \text{ cm}^{-1}$ ,  $D = -5.3 \text{ cm}^{-1}$ ,  $E/D = 0.13$ , and  $g = 2.02$ , indicating that there is no significant exchange coupling interaction (Figure S5).

Dissolution of **2** in THF, followed by recrystallization, affords compound **3** (Scheme 1). The structure (Figure S5) reveals two different diiron(II) units, with composition  $[\text{Fe}_2(\mu\text{-O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{THF})_2]^{11}$  (**3a**) and  $[\text{Fe}_2(\text{OH}_2)_2(\mu\text{-O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{THF})_2]^{11}$  (**3b**).<sup>21</sup> Both of these compounds have been previously reported, with **3a** being formally derived from **3b** by loss of two water molecules.

A proposed, speculative pathway for interconverting the five iron(II) compounds is presented in Scheme 1. The complete disruption of the  $[\text{Fe}_2(\mu\text{-O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{THF})_2]^{11}$  complex by the addition of excess water results in the fully hydrated ferrous ion, the charge of which is compensated in the solid state by the carboxylate anions through electrostatic and hydrogen bonding interactions. When less water is added, diiron(II) complex **2**, with three aqua ligands, two in bridging positions and one in a terminal site, is generated. The related complex,  $[\text{Fe}_2(\text{OH}_2)_2(\mu\text{-O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{O}_2\text{CAR}^{4\text{F-Ph}})_2(\text{THF})_2]^{11}$  to afford **3**, in which the average number of water molecules is one per diiron(II) unit. These five iron(II) compounds strongly suggest the occurrence of water-dependent equilibria in the solution.

The present results thus reveal that carboxylate-rich diiron(II) units can accommodate diverse geometries depending on the amount

of water available. This water-dependent behavior may derive from the special ability of carboxylate ligands to undergo carboxylate shifts and has thus far not been encountered in diiron(II) complexes with nitrogen-rich coordination environments. The diiron active sites in sMMOH,<sup>10</sup> RNR-R2,<sup>6</sup>  $\Delta$ -9D,<sup>7</sup> and ToMOH<sup>8</sup> contain variable amounts of water in the first and second coordination spheres. The diiron(II) center of sMMOH has two water molecules compared with no water at all at the diiron(II) core of  $\Delta$ -9D. Perhaps the accessible amount of water in non-heme diiron(II) enzymes is a control element for achieving diverse functions using a shared structural motif. Although our study clearly demonstrates that solution water levels can dictate the core structures and composition of isolable carboxylate-rich diiron(II) complexes, a more quantitative treatment and understanding of the influence of water on the oxygenation events remain for future work.

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**Supporting Information Available:** Details of the synthetic procedures, physical characterization of **2**, ORTEP diagrams of compounds **1–3**, and X-ray crystallographic files for these compounds (PDF, CIF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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