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An Oxidized Active Site Model for the FeFe Hydrogenase: Reduction with Hydrogen Gas

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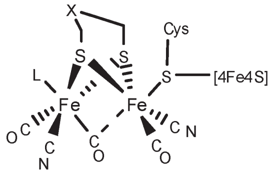
Supporting Information

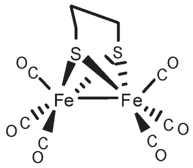
ABSTRACT: Models for the oxidized form of the FeFe hydrogenase active site have been prepared. These cationic complexes contain two iron atoms, carbonyl ligands, a propanedithiolate bridge, and one other bridging group. Reduction of these complexes with hydrogen gas is demonstrated.

Hydrogenase enzymes catalyze the oxidation of dihydrogen and the reduction of protons in nature. X-ray crystallography and IR spectroscopy of the FeFe hydrogenases have shown the active site to be comprised of a [2Fe2S] subunit linked to a [4Fe4S] cluster by a cystenyl-S bridge.[1,2] The two iron atoms in the [2Fe2S] subunit are linked by a bridging dithiolate ligand and are ligated by the biologically uncommon ligands carbon monoxide (CO) and cyanide (CN^-).[3] Other features of the enzyme include channels for proton and gas transport and a chain of [4Fe4S] clusters for electron distribution.



Active site

L = H_2 or H_2O; X = N?



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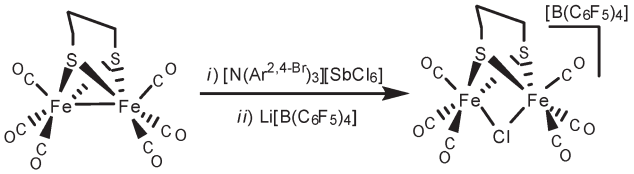
The crystal structure of $Fe_2(\mu\text{-}S_2C_3H_6)(CO)_6$ (**1**) has been reported; the structural resemblance to the active site of the FeFe hydrogenase was noted by Darensbourg and co-workers.[4] A number of active site model complexes have been reported, including a very interesting Fe_2S_3 model system which mimics the active site with a pendant thioether moiety.[5] In related work, electrocatalytic H_2 oxidation has been demonstrated at a graphite electrode impregnated with a NiFe hydrogenase.[6] The efficiency of the electrocatalysis was comparable to Pt electrodes. A photocathode functionalized with an H-cluster analogue has also been demonstrated.[7,8]

A number of reduced synthetic models of the FeFe hydrogenase are reported to react with acids to form dihydrogen.[9] Several reports have described the reduction chemistry of **1**. For example, Darensbourg et al. reported that the reduction of **1** led to hydrogen evolution in the presence of acetic acid.[10] Pickett and co-workers reported hydrogen evolution from protic media catalyzed by complex **1** under reducing conditions.[11]

Models for the oxidized form of the active site have been less studied. In contrast to facile and reversible reduction, CV shows that **1** is oxidized only with difficulty and irreversibly.[12] Advances in oxidation chemistry have been demonstrated in a phosphine-containing system that reacts with hydrogen and silanes photochemically.[13] In di-iron models with bridging hydride ligands, photochemical reactions with H_2 have been assayed by scrambling of D_2 to form HD.[14] The chemical oxidation with halogens of complexes similar to **1** leads to Fe—Fe bond cleavage, but the products were not structurally characterized.[15] Diferrous complexes resembling **1** have been prepared with cyanide and isonitrile ligands, but neither are reported to react with hydrogen.[16,17] Some Fe(I)—Fe(II) mixed oxidation species have also been reported, including one example which reacts with hydrogen.[18] Here, we report our studies of the chemical oxidation of **1**, which afford well-characterized cationic diferrous species which can be reduced with hydrogen gas.

We find that the oxidation of **1** is cleanly achieved with $[N(Ar^{2,4\text{-}Br})_3][SbCl_6]$ in CH_2Cl_2. Anion metathesis with $Li[B(C_6F_5)_4]$ in CH_2Cl_2 yields $[Fe_2(\mu\text{-}Cl)(\mu\text{-}S_2C_3H_6)(CO)_6][B(C_6F_5)_4]$ (**2**) as orange crystals in 78% yield (Figure 1).[19]



1

2

The infrared spectrum (KBr) of **2** in the carbonyl region indicates an oxidized species, with five bands at 2142, 2125, 2094, 2059, and 2046 cm^{-1}.

Complex **2** is diamagnetic; the ^1H NMR spectrum exhibits resonances for the propane dithiolate bridge at δ 2.46 (4H, t) and 1.90 (2H, quint). An X-ray diffraction study of **2** revealed an Fe—Fe distance of 3.005 Å, consistent with oxidation to a diferrous state and a loss of the Fe—Fe bond (Figure 1). The structure resembles diferrous dimers such as $[Fe_2(\mu\text{-}SMe)_3(CO)_6]^+$ (Fe—Fe distance 3.06 Å) and $[Fe_2(\mu\text{-}SMe)_3(CO)_4(PPhMe_2)_2]^+$ (Fe—Fe 3.07 Å)[20] but is longer than that observed in $Fe_2(\mu\text{-}S_2C_2H_4)(\mu\text{-}CO)(PR_3)_2(CN)_2(CO)_2$ (Fe—Fe 2.55 Å) and related dicationic species (Fe—Fe distances 2.49—2.63 Å).[14,15] The Fe—Fe distance in **1** is 2.510 Å.[4]

Complex **2** does not react with Ag^+ or Na^+ salts at room temperature. Surprisingly, complex **2** fails to react with the

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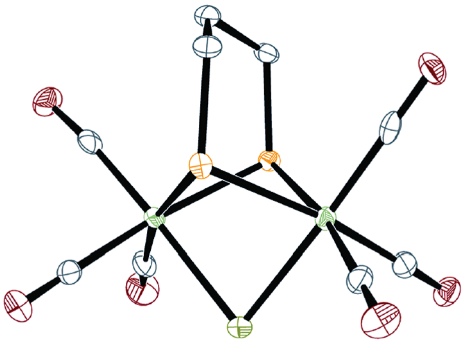


Figure 1. ORTEP diagram of **2**. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and $B(C_6F_5)_4$ counterion omitted for clarity.

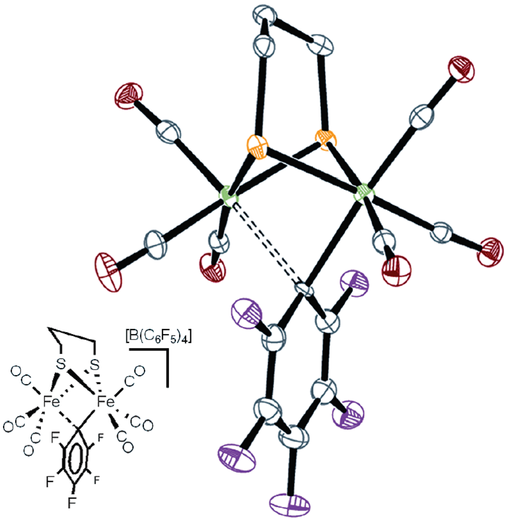
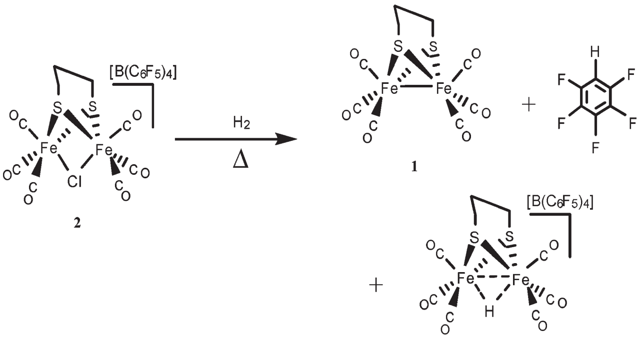


Figure 2. ORTEP diagram of **3**. Thermal ellipsoids are drawn at 50% probability. Hydrogen atoms and the $B(C_6F_5)_4$ counterion omitted for clarity. A schematic diagram is included to elucidate the structure.

powerful chloride abstracting reagent $[Et_3Si][B(C_6F_5)_4]$. Reduction with the hydride donor $LiHBEt_3$ rapidly forms complex **1** with evolution of the hydrogen gas. Over the course of several hours at room temperature, the reaction of $HSiEt_3$ with complex **2** affords complex **1**, accompanied by hydrogen evolution. Formation of $ClSiEt_3$ was confirmed by ^{29}Si NMR spectroscopy.

The reduction of complex **2** can be achieved with hydrogen. The heating of **2** in fluorobenzene to 70 °C under 1 atm of hydrogen gas results in reduction to **1** as well as the formation of C_6F_5H and small amounts (*ca.* 5%) of the previously reported cationic bridging hydride $[Fe_2(\mu\text{-}H)(\mu\text{-}S_2C_3H_6)(CO)_6][B(C_6F_5)_4]$.[21]



Repeating the reaction with D_2 gas and monitoring by ^2H NMR spectroscopy led to the detection of the presence of DC_6F_5 and the cationic bridging deuteride. The presence of deuterium in the reaction products confirms that H_2 (D_2) is the reductant. The fluorobenzene solvent also incorporates deuterium in the course of this reaction, consistent with the fluorine substituent activating proton exchange.[22]

The observation of C_6F_5H in the reduction reaction suggests that activation of the fluorinated tetraphenylborate counteranion has occurred. When **2** is heated in fluorobenzene under argon, a slow reaction takes place that can be inhibited by the addition of an atmosphere of CO gas. Reaction is complete after heating at 70 °C for 72 h. The ^1H NMR spectrum exhibits new propanedithiolate signals at δ 2.40 (4H, t) and 2.01 (2H, quintet). Layering with pentane yields red crystals of complex **3** (43% yield). Complex **3** exhibits IR bands (KBr) in the carbonyl region at 2117, 2082, and 2062 cm^{-1}, consistent with an oxidized species.

The structure was determined by X-ray diffraction and confirms the formulation as $[Fe_2(\mu\text{-}C_6F_5)(\mu\text{-}S_2C_3H_6)(CO)_6][B(C_6F_5)_4]$ (**3**). The Fe—Fe distance in **3** is 2.803 Å (Figure 2).[23] The bridging chloride ligand has been replaced with the C_6F_5 group that forms an asymmetric bridge between the iron atoms. The Fe—C distances observed are 2.188(2) and 2.318(3) Å.

Reactions of the $B(C_6F_5)_4$ anion are unusual; Reed et al. has reported boron—carbon bond cleavage in this anion under superacidic conditions.[24] This reaction is observed more commonly with tetrakis(bis-3,5-(trifluoromethyl)phenyl)borate anions.[25]

Heating a sample of **3** under hydrogen gas gave the same product distribution as the hydrogen reduction of **2**, suggesting that **3** may be an intermediate in the reduction reaction. We propose that complex **3** is formed after the initial CO loss, consistent with inhibition by CO gas. The highly Lewis acidic pentacarbonyl fragment can react with the $B(C_6F_5)_4$ counterion or with H_2. Our data do not distinguish secondary hydrogenation of **3** from direct coordination of H_2 to the pentacarbonyl fragment derived from **2**. In both cases, a reaction with hydrogen gas ensues, resulting in overall reduction of the iron centers to Fe(I) (after deprotonation). Pentacarbonyl fragments derived from complexes **2** and **3** could resemble the structure of the oxidized H cluster.

Further studies are underway to detect dihydrogen intermediates in the reduction reaction and to employ less reactive counteranions.

■ ASSOCIATED CONTENT

Ⓢ **Supporting Information.** Experimental details and details of characterization of new compounds. X-ray crystallographic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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NOTE ADDED IN PROOF

Mild oxidation of a FeFe hydrogenase active site model has been shown to enhance reactivity with hydrogen: Camara, J. M.; Rauchfuss, T. B. *J. Am. Chem. Soc.* **2011**, *133*, 8098−8101.