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Active-Site Models for Iron Hydrogenases: Reduction Chemistry of Dinuclear Iron Complexes

Inigo Aguirre de Carcer,[†] Antonio DiPasquale,[‡] Arnold L. Rheingold,[‡] and D. Michael Heinekey*,[†]

Department of Chemistry, University of Washington, Seattle, Washington 98195-1700, and
Department of Chemistry and Biochemistry, University of California at San Diego,
La Jolla, California 92093-0332

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Reduction of $Fe_2(\mu\text{-}S_2C_3H_6)(CO)_6$ (**1**) in tetrahydrofuran with 1 equiv of decamethylcobaltocene ($Cp^*{}_2Co$) affords a tetranuclear dianion **2**. The IR spectra of samples of **2** in solution and in the solid state exhibit a band at 1736 cm^{-1}, suggestive of the presence of a bridging carbonyl (CO) ligand. X-ray crystallography confirms that the structure of **2** consists of two Fe_2 units bridged by a propanedithiolate moiety formulated as $[Fe_2(\mu\text{-}S_2C_3H_6)(CO)_5(SCH_2CH_2CH_2\text{-}\mu\text{-}S)Fe_2(\mu\text{-}CO)(CO)_6]^{2-}$. One of the Fe_2 units has a bridging CO ligand and six terminal CO ligands. The second subunit exhibits a bridging propanedithiolate moiety. One CO ligand has been replaced by a terminal thiolate ligand, replicating the basic architecture of Fe-only hydrogenases. The reduction reaction can be reversed by treatment of **2** with 2 equiv of $[Cp_2Fe][PF_6]$, reforming complex **1** in near-quantitative yield. Complex **2** can also be oxidized by acids such as *p*-toluenesulfonic acid, regenerating complex **1** and forming H_2.

Recent crystallographic studies of the iron hydrogenase enzymes[1] show that the active site contains a novel Fe_2 moiety. Unidentified diatomic ligands were ultimately shown to be carbonyl (CO) and cyanide (CN) ligands by IR spectroscopy.[2] Activation of H_2 is believed to occur at a vacant site formed by loss of weakly bound water. Inhibition of enzymatic activity by CO binding to this site has been demonstrated, and the structure of the CO-bound form has been determined.[3] The proposed dithiolate bridge cannot be definitively characterized from the crystallographic data on the enzymes. A propanedithiolate or an azapropanedithiolate structure with a central N atom has been suggested. Computational studies[4] favor the latter possibility in that a smooth pathway for heterolysis of bound H_2 is possible via proton transfer to the adjacent N atom. More recent crystallographic work is also consistent with this hypothesis.[5]

Several model systems for this active site based on well-studied organometallic precursors have been investigated.[6] Darensbourg and co-workers reported the crystal structure of $Fe_2(\mu\text{-}S_2C_3H_6)(CO)_6$ (**1**) and pointed out its close structural resemblance to the enzyme active site.[7] Rauchfuss and co-workers have reported that reaction of **1** with CN affords $[Fe_2(\mu\text{-}S_2C_3H_6)(CO)_4(CN)_2]^{2-}$. This dicyano species is readily oxidized to insoluble materials.[8] A very promising Fe_2S_3 model system that mimics the active site with a pendant thioether moiety attached to the central C atom of a propanedithiolate bridging ligand has been reported by Pickett and co-workers. Interestingly, with this ligand system, a transient bridging CO species is formed upon reaction with CN.[9] This is a very significant observation because the existence of a bridging CO ligand in some redox states of the enzyme has been clearly demonstrated by IR spectroscopy.[2,5] Definitive evidence for bridging CO ligands in model complexes has been very limited, with the only isolable complexes being isonitrile[10] and cyanide[11] derivatives reported by Rauchfuss and co-workers. Interesting model

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* To whom correspondence should be addressed. E-mail: heinekey@chem.washington.edu.

[†] University of Washington.

[‡] University of California at San Diego.

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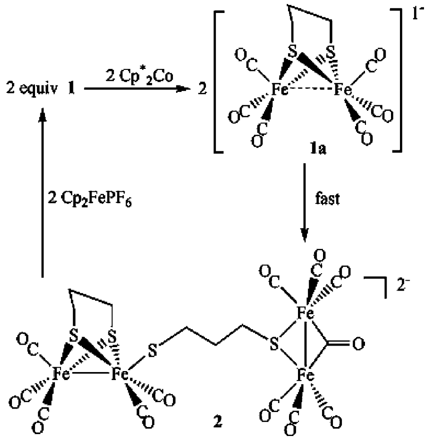
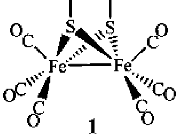
Scheme 1



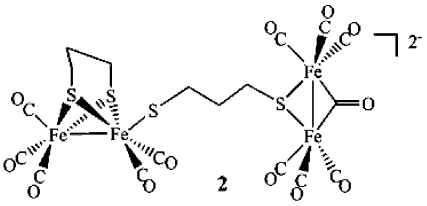
complexes with azadithiolate bridging ligands have recently been prepared by a novel synthetic approach.[12] Model complexes with azadithiolate and phosphine ligands have been shown to form a briding hydride *and* protonate at the bridiging N atom.[13]

Several reports have described the reduction chemistry of **1**, with somewhat conflicting results. A reversible two-electron reduction of complex **1** in dimethylformamide under CO was previously reported based on cyclic voltammetry (CV) studies.[14] A recent report by Darensbourg and co-workers using CV and bulk electrolysis studies in CO-saturated CH_3CN is consistent with an initial one-electron reduction at -1.34 V (vs NHE), with a subsequent one-electron reduction to a dianion occurring only at -1.95 V.[15] Darensbourg also reported that the reduced species led to H_2 evolution in the presence of acetic acid. Pickett and co-workers recently reported that H_2 evolution from protic media catalyzed by complex **1** under reducing conditions is comprised of two processes with measured onsets at -1.34 and -1.56 V.[16]

Pickett and co-workers also reported the detailed study of a one-electron-reduction product formulated as **1a** (see Scheme 1) and the subsequent chemistry of this complex, which includes a proposed disproportionation/ligand redistribution reaction that affords a dimeric species containing four Fe atoms. The structure of this molecule depicted below as **2** was proposed based on limited spectroscopic data because the complex could not be isolated.



1



2

We report herein our studies of the chemical reduction of **1**, which allows for the isolation and structural characterization of the previously postulated complex **2**.

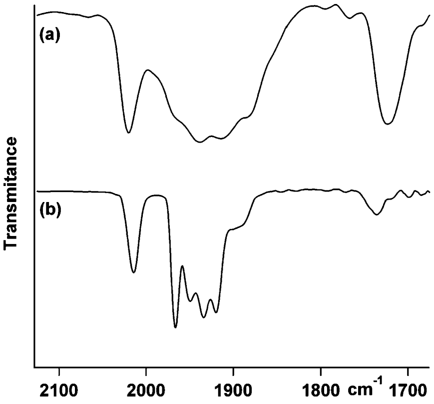


Figure 1. Partial IR spectra (CO stretching region) of complex **2**: (a) solid state; (b) solution in THF.

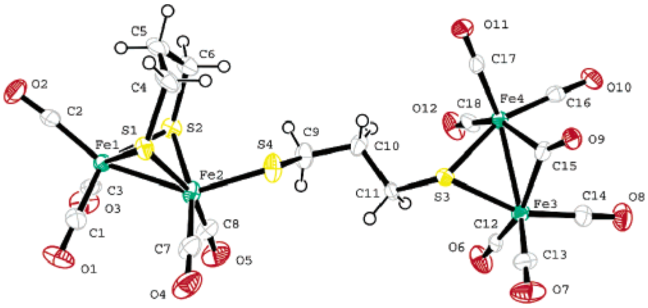


Figure 2. ORTEP diagram of the anionic portion of **2** (50% thermal ellipsoids). Selected bond distances (Å): Fe1−Fe2, 2.5075; Fe2−S4, 2.280; Fe3−Fe4, 2.5224.

Reduction of tetrahydrofuran (THF) solutions of complex **1** with 1 equiv of Cp*$_2$Co leads to clean formation of a new species **2** in seconds at room temperature. Complex **2** was isolated as the bis-Cp*$_2$Co$^+$ salt by the addition of diethyl ether.[17] The IR spectrum of **2** in the CO region consists of five intense bands at 2014, 1967, 1950, 1934, and 1919 cm^{-1} corresponding to terminal CO ligands and one lower energy band at 1736 cm^{-1} consistent with the presence of a bridging CO group (see Figure 1).

Crystals of **2** suitable for X-ray diffraction were obtained by filtration of the THF solution described above followed by layering with diethyl ether.[18] The structure of **2** consists of two Fe_2 units connected by a propanedithiolate bridge. One of the Fe_2 units has a bridging CO ligand and six terminal CO ligands, while the other has five CO ligands, a

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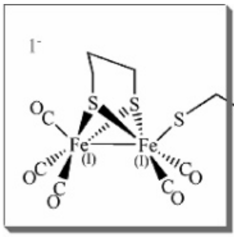
(17) Elem anal. Calcd for $C_{58}H_{72}Co_2Fe_4O_{12}S_4$: C, 48.68; H, 5.08; S, 8.96. Found: C, 48.50; H, 5.30; S, 8.99.

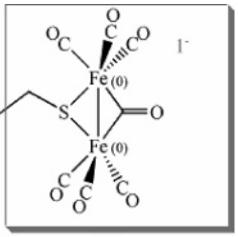
(18) Crystal data for **2**: $C_{58}H_{72}Co_2Fe_4O_{12}S_4$, brown plate, 20 × 20 × 5 μm, triclinic, $P1$ (No. 2), $Z = 2$, $a = 9.163(6)$ Å, $b = 19.047(13)$ Å, $c = 20.123(14)$ Å, $V = 3064(4)$ Å^3, $\mu = 1.645$ mm^{-1}, $D_{calc} = 1.550$ g/cm^3, R1 = 0.0467, wR2 = 0.0890. Data collection: Bruker Smart CCD system, $T = 100$ K, Mo Kα ($\lambda = 0.710\ 73$ Å), 31 845 reflections, 10 761 unique reflections. The data were corrected for absorption; the structure was solved by direct methods; all non-H atoms were refined anisotropically by full-matrix least squares (*SHELXL-97*); all H atoms were placed using a riding model and their positions constrained relative to their parent atom.

propenedithiolate bridge, and a terminal thiolate ligand (see Figure 2).

The structure of complex **2** is most conveniently considered in two parts, labeled as **2a** and **2b** in the representation below. If we assume that each Fe dimer moiety carries a single negative charge, then **2a** consists of two *formally* Fe^I atoms at a bond distance of 2.5075(16) Å. This Fe−Fe bond distance and all other structural parameters in **2a** are very similar to those from X-ray crystallography for the active site of the Fe-only hydrogenase enzymes.[1] With five terminal diatomic ligands and differential S ligation at the Fe atoms, **2a** is a rare example of an anionic monosubstituted thiolate diiron pentacarbonyl that replicates the basic architecture of the enzyme.



2a



2b

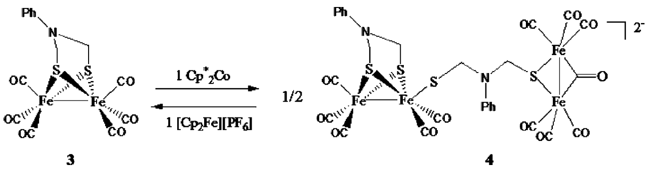
A complex closely related to the heptacarbonyl moiety **2b** has been previously isolated by Pickett and coworkers by reduction of **1** under CO with $Li(HBEt_3)$.[16] By this procedure, a propanethiol salt $[Fe_2(\mu\text{-}CO)(CO)_6(\mu\text{-}SCH_2CH_2CH_2SH)][Li]$ was prepared. The spectroscopic similarity of this complex to the electrode reduction product is apparent.[16] Like **2b**, the Pickett complex is diamagnetic with both Fe atoms formally in the zero oxidation state.

Complex **2** is readily oxidized using a ferricenium ion. Thus, reaction of dianion **2** in THF with 2 equiv of $[Cp_2Fe][PF_6]$ affords complex **1**. The complete reaction sequence can be conveniently monitored by IR spectroscopy (see the Supporting Information), which indicates a 90% yield for the overall reaction (Scheme 1).

Rapid CO substitution reactions of hexacarbonylmetal-bridged dimers of Co and Fe have been reported upon chemical or electrochemical reduction.[14,19] The initial reduction of these complexes populates an antibonding metal−metal orbital; odd electron metal fragments are generated and can be readily substituted in the presence of a suitable ligand. Consistent with the electrochemical studies of Pickett and co-workers, we postulate that an initial one-electron reduction of **1** leads to a very short-lived species **1a**. Formation of **2** from **1a** on the time scale observed requires rapid substitution of a CO ligand by a thiolate and efficient capture of the CO ligand, accompanied by electron transfer between the Fe dimers.

Our observations support the proposal of Pickett and co-workers that one-electron reduction of **1** can be followed by a rapid bimolecular disproportionation reaction accompanied by extensive ligand redistribution. Given the extensive ligand rearrangement involved in the formation of **2**, it is quite surprising that these reactions are readily reversible upon oxidation. The very rapid formation of **2** upon reduction of **1** and the facile oxidation of complex **2** to yield **1** suggest that the electrode chemistry of **1** may also be affected by the formation of complex **2**. We find that complex **2** can also be oxidized by *p*-toluenesulfonic acid ($pK_a = 8$ in CH_3CN),[20] regenerating complex **1** and forming H_2. This observation suggests a possible role for complex **2** in the reported electrocatalytic evolution of H_2 observed in the presence of **1**.[15,16]

Scheme 2



We find that reduction of the closely related bridging azadithiolate complex $Fe_2(\mu\text{-}SCH_2NPhCH_2S\text{-}\mu)(CO)_6$ (**3**) gives similar results[21] (Scheme 2). Complex **3** differs from **1** in that the central CH_2 moiety of the propyl bridge is replaced with a NPh group. Reaction of **3** with Cp*Co affords a new complex **4**. The IR spectrum of **4** consists of five intense bands at 2021, 1969, 1960, 1936, and 1920 cm^{-1} and a bridging band at 1738 cm^{-1}. The ^1H NMR spectrum of **3** exhibits aromatic resonances (10H) and aliphatic resonances (8H) due to the methylene bridges (see the Supporting Information). The spectroscopic data for **4** suggest a structure similar to that of **2**.

Oxidation of **4** with 2 equiv of $[Cp_2Fe][PF_6]$ affords complex **3** in 70% yield. Complex **4** can also be oxidized by *p*-toluenesulfonic acid, regenerating complex **3** and H_2 gas. The yield of **3** in these reactions is consistently inferior to the yield of **1** obtained by oxidation of **2**. Oxidation of **4** is accompanied by substantial decomposition reactions to unidentified products.

We conclude that insights as to the active-site structure of the iron hydrogenases can be gained by the study of simple analogues such as **1**, but the reduction chemistry of these complexes is much more complicated than previously thought. We are continuing to study related molecules with the goal of developing efficient catalysts for the electrocatalytic production of H_2.

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Supporting Information Available: Experimental details and X-ray crystallographic data (CIF) for **2**. This material is available free of charge via the Internet at http://pubs.acs.org.

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