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Unsaturated, Mixed-Valence Diiron Dithiolate Model for the H_{ox} State of the [FeFe] Hydrogenase**

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The [FeFe] hydrogenase enzymes are the most efficient catalysts known for the reduction of protons to H₂.^[1] The active site exists in two functional states (Scheme 1), H_{red}, which is $S = 0$, and H_{ox}, which is $S = 1/2$.^[2] Research in this area is aimed at elucidating the mechanism of the enzymatic catalysis and at using this information to develop protein-free bioinspired synthetic catalysts.^[3] A specific research goal is the preparation of molecules that resemble the functional states of the active site with the expectation that function will follow form. Most studies on diiron dithiolato carbonyl complexes rely on organic ligands (e.g. phosphanes) in place of the naturally occurring cyanide and μ -SR[Fe₄S₄] ligands,^[4] which have complicated acid–base behavior that is often difficult to control outside of the protein. Another barrier to modeling has been the rarity of mixed-valence diiron dithiolate compounds with the appropriate structures, stability, and reactivity.

The first evidence for mixed valency in diiron dithiolate models was obtained in the one-electron oxidation of [Fe₂{(SCH₂)₂CMeCH₂SMe}(CN)₂(CO)₄]²⁻, which afforded a thermally sensitive mixed-valence derivative with IR and EPR spectroscopy signatures resembling those for the CO-inhibited enzyme.^[5] In very recent work, the oxidation of [Fe₂(S₂C₃H₆)(CO)₄(PMe₃)L¹] (L¹ = 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene) was shown to give a mixed-valence derivative with structural and spectroscopic features resembling H_{ox}.^[6]

Our recently reported species [Fe₂(S₂C₂H₄)(CO)₃(PMe₃)-(dppv)] (**1**, dppv = *cis*-1,2-C₂H₂(PPh₂)₂) is attractive, because, like the active site, this diiron framework bears three donor ligands and three CO ligands.^[7] We previously showed that oxidation of **1** in MeCN gives [1(NCMe)]²⁺. In MeCN solution, one equivalent of oxidizing agent gives an approximately 1:1 mixture of unreacted starting material and [1(NCMe)]²⁺. Oxidation of **1** in the weakly coordinating solvent CH₂Cl₂, however, proceeds quite differently.

Addition of one equivalent of FcBF₄ (Fc⁺ = [Fe(C₅H₅)₂]⁺) to a CH₂Cl₂ solution of **1** at –45 °C resulted in complete consumption of the diiron complex, as indicated by in situ IR spectroscopy. We probed the oxidation of **1** by cyclic voltammetry on a solution of **1** in 0.1M

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Bu₄NPF₆/CH₂Cl₂. The voltammetry revealed a reversible couple at 20 mV vs. Ag/AgCl (ca. 300 mV vs. NHE). No other redox events were observed between 0.6 and -1 V.

The purple-colored compound **1**-BF₄ is stable in solution for several minutes at room temperature and is sufficiently stable that we were able to grow single crystals for X-ray diffraction (see below). The X-band EPR spectrum of polycrystalline **1**-BF₄ (15 K) displays *g* values at 2.14, 2.03, 2.01 as well as a signal for an apparent impurity at *g* = 2.05; this rhombic pattern is similar to that seen for H_{ox} from *D. desulfuricans* (*g* = 2.10, 2.04, 1.99).^[1,8]

Crystals of **1**-BF₄ were obtained from CH₂Cl₂/hexanes at -20 °C. Crystallographic analysis revealed an unsolvated 1:1 salt. In general, the [Fe₂(SR)₂L₆] framework approaches that proposed for the H_{ox} state of the active site.^[2,9] Of specific interest, the oxidation has caused the {Fe(CO)(dppv)} center to rotate about the Fe-Fe axis. The apical site on the {Fe(dppv)} center is vacant, and the [BF₄]⁻ anion is approximately 5 Å away from this “distal” Fe center. The “proximal” {Fe(CO)₂(PMe₃)} moiety remains relatively unperturbed, and overall the bond lengths match those in **1** within 0.02 Å.^[7] The unique CO ligand is only partially bridging, with a relatively long Fe_{prox}-C separation of 2.62 Å compared to the Fe_{dist}-CO bond length of 1.781(3) Å (∠(Fe_{dist}-C-O) = 170.2(3)°; Figure 1). We have recently described [Fe₂-(S₂C₂H₄)(CO)(μ-COAX₃)(dppv)₂] (AX₃ = AlBr₃, B(C₆F₅)₃), which is not mixed-valence but also adopts the rotated structure.^[10]

The unsaturated character of **1**-BF₄ is indicated by the speed of its reaction with CO, which occurs in seconds at -45 °C. The product is proposed to be the adduct [1(CO)]BF₄ (Scheme 2). The carbonylation is indicated by a shift of the ν_{CO} bands (2021, 1970, 1883 cm⁻¹ to 2030, 1987, 1783 cm⁻¹; see Table 1); the band for the bridging CO ligand (ν_{μ-CO}) shifts by 100 cm⁻¹. This dramatic shift for the bridging CO group is possibly due to the ligand moving into a bridging position from a bent-semibridging position. The spectrum of [1(CO)]BF₄ matches that seen by Pickett upon oxidation of [Fe₂{(SCH₂)₂CMeCH₂SMe}(CN)₂(CO)₄]²⁻.^[5] The observation of only three ν_{CO} bands for this tetracarbonyl species results from accidental degeneracy: the 1987 cm⁻¹ band arises from both the {Fe(dppv)(CO)_{terminal}} site and the asymmetric component of the {Fe(CO)₂(PMe₃)} site. Carbonylation of **1**-BF₄ with ¹³CO resulted in the appearance of one new band in the IR spectrum (Figure 2), which is consistent with regioselective labeling. This new band is proposed to arise from the splitting of the 1987 cm⁻¹ band in **1** (see above). Significantly, ν_{μ-CO} is barely affected (3 cm⁻¹). In general, the ν_{CO} bands for the terminal CO ligands in both **1**-BF₄ and [1(CO)]BF₄ are higher in energy than those for H_{ox}.^[1,2] The IR spectra for **1**-BF₄ and [1(CO)]BF₄ bear a resemblance to the patterns seen for the enzyme from *D. desulfuricans*.^[11]

An N₂ purge slowly (0 °C, 30 min) displaced CO from [1(CO)]BF₄ to give **1**-BF₄ with only moderate decomposition. A stable tetracarbonyl compound was generated by treating [1(CO)]BF₄ with FcBF₄. This reaction afforded the diamagnetic dication [1(CO)]²⁺, which was isolated in analytical purity as its tetrafluoroborate salt. NMR spectroscopy data indicate that [1(CO)]²⁺ has C_s symmetry (Scheme 2). Under an atmosphere of CO, [1(CO)]²⁺ is stable for hours at room temperature.

The radical character of **1**-BF₄ was demonstrated by its reactivity toward NO. At -45 °C, **1**-BF₄ rapidly and irreversibly binds NO. The product, which forms with loss of CO, is the diamagnetic dicarbonyl nitrosyl [Fe₂(S₂C₂H₄)(CO)₂(NO)(PMe₃)(dppv)]BF₄ (ν_{NO} = 1772 cm⁻¹), which was isolated in analytical purity. ¹H and ³¹P NMR spectra show that this {Fe^I₂} species is C_s-symmetric, which uniquely requires that the NO ligand occupies the apical site on the {Fe(dppv)} center (Scheme 2).

In summary, the mixed-valence salt $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]\text{BF}_4$ displays the structure and reactivity proposed for H_{ox} , one of the two functional states of the $[\text{FeFe}]$ hydrogenases.^[1] Future reports will describe further spectroscopic characterization of this new generation of model complexes.

Experimental Section

$[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]\text{BF}_4$, **1-BF₄**: A solution of **1** (0.400 g, 0.526 mmol) in CH_2Cl_2 (5 mL) at -45°C was treated with a solution of FcBF_4 (0.143 g, 0.526 mmol) in CH_2Cl_2 (15 mL). The resulting purple solution was transferred into hexanes (200 mL) cooled to -45°C to precipitate the product. Crystals were grown via slow diffusion of hexanes into a methylene chloride solution at -20°C . Yield 0.15 g (34%). The low yield is attributed to mechanical losses due to the large volume flask required for the precipitation. The method was optimized for the removal of the ferrocene coproduct, not yield. In situ IR measurements indicate that the conversion is virtually quantitative. IR (CH_2Cl_2): $\nu_{\text{CO}} = 2021$ (vs), 1970 (s), 1883 cm^{-1} (m, br). Elemental analysis calcd for $\text{C}_{34}\text{H}_{35}\text{BF}_4\text{Fe}_2\text{O}_3\text{P}_3\text{S}_2$: C 48.20, H 4.16; found: C 47.33, H 4.27.

Carbonylation of $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]\text{BF}_4$: A solution of **1** (0.050 g, 0.066 mmol) in CH_2Cl_2 (5 mL) at -45°C was treated with a solution of FcBF_4 (0.018 g, 0.066 mmol) in CH_2Cl_2 (2 mL). In situ IR spectra confirmed the formation of $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]\text{BF}_4$. Maintaining the solution at -45°C , the solution was treated with a stream of CO (ca. 0.1 mLs^{-1} for 1 min) with no precautions to exclude ambient light. IR (CH_2Cl_2): $\nu_{\text{CO}} = 2030$ (s), 1987 (vs), 1783 cm^{-1} (m, br). The ^{13}C labeling experiment was conducted similarly.

$[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_4(\text{PMe}_3)(\text{dppv})](\text{BF}_4)_2$: A solution of **1** (1.0 g, 1.31 mmol) in CH_2Cl_2 (10 mL) at -45°C was treated with a solution of FcBF_4 (0.71 g, 2.63 mmol) in CH_2Cl_2 (10 mL) under a CO atmosphere. The solution was allowed to warm to room temperature under a CO atmosphere and concentrated to 5 mL. The brown solid precipitated upon addition of 40 mL of hexanes. Yield: 0.98 g (91%). ^1H NMR (500 MHz, CD_2Cl_2): $\delta = 8.8\text{--}7.3$ (m, 20H; C_6H_5), 4.2 (s, 2H; PCH), 3.5 (m, 2H; SCH₂), 2.0 (d, $J_{\text{PH}} = 12$ Hz, 9H; PCH₃), 1.4 ppm (m, 2H; SCH₂). ^{31}P NMR (202 MHz, CD_2Cl_2): $\delta = 68.0$ (d, $J_{\text{PP}} = 3$ Hz), 38.2 ppm (t, $J_{\text{PP}} = 3$ Hz). IR (CH_2Cl_2): $\nu_{\text{CO}} = 2063, 2028, 1939\text{ cm}^{-1}$. Elemental analysis calcd for $\text{C}_{35}\text{H}_{35}\text{B}_2\text{F}_8\text{Fe}_2\text{O}_4\text{P}_3\text{S}_2$: C 43.70, H 3.67; found: C 43.82, H 3.81.

$[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_2(\text{NO})(\text{PMe}_3)(\text{dppv})]\text{BF}_4$: A solution of $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]$ (0.050 g, 0.066 mmol) in 5 mL of CH_2Cl_2 at -45°C was treated with a solution of FcBF_4 (0.018 g, 0.066 mmol) in CH_2Cl_2 (2 mL). An in situ IR spectrum of the reaction mixture showed $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]^+$ in solution. The reaction mixture was treated with a stream of NO and after 1 min the IR spectrum showed complete conversion to $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{NO})(\text{PMe}_3)(\text{dppv})]^+$, which was spectroscopically identical to a sample prepared from the reaction of **1** and NOBF_4 . ^1H NMR (500 MHz, CD_2Cl_2): $\delta = 8.8\text{--}7.3$ ppm (m, 20H; C_6H_5). ^{31}P NMR (202 MHz, CD_2Cl_2): $\delta = 74.1, 25.0$ ppm. IR (CH_2Cl_2): $\nu_{\text{CO}} = 2002, 1955\text{ cm}^{-1}$; $\nu_{\text{NO}} = 1772\text{ cm}^{-1}$. ESI-MS: m/z 762.2 ($[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_2(\text{NO})(\text{PMe}_3)(\text{dppv})]^+$). Elemental analysis calcd for $\text{C}_{33}\text{H}_{35}\text{BF}_4\text{Fe}_2\text{NO}_3\text{P}_3\text{S}_2$: C 46.67, H 4.15, N 1.65; found: C 46.66, H 4.37, N 1.62.

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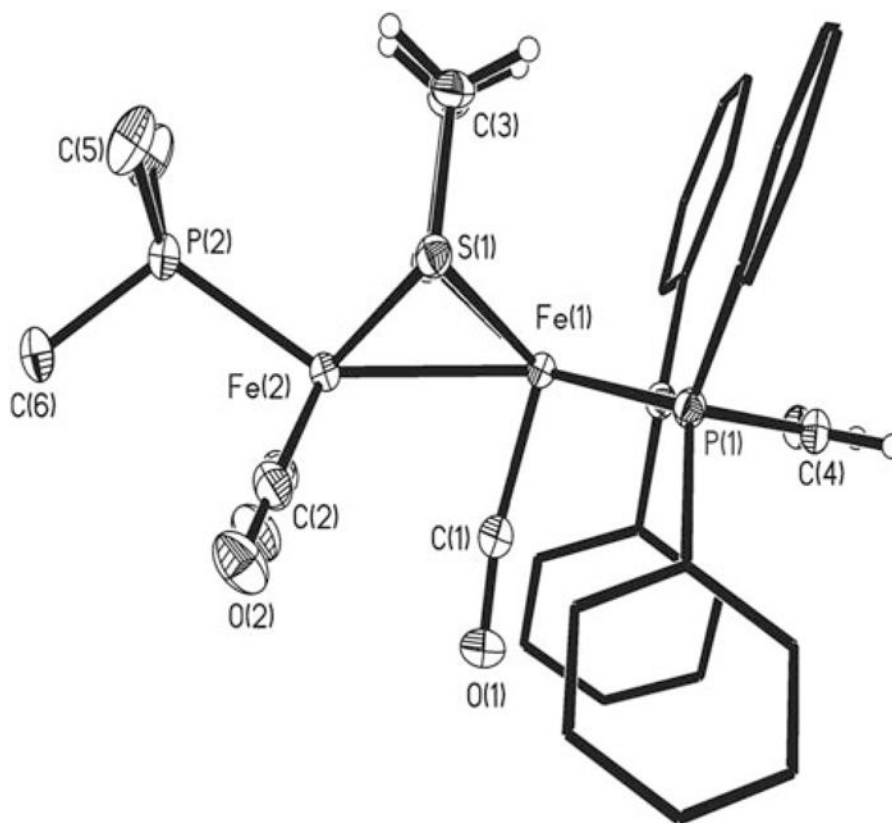


Figure 1. Structure of the cation in $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]\text{BF}_4$ with thermal ellipsoids set at the 30% probability level. For clarity, methyl and phenyl hydrogen atoms are omitted. Selected distances [\AA] and angles [$^\circ$]: Fe(1)-Fe(2) 2.5598(5), Fe(1)-S(1) 2.2742(5), Fe(2)-S(1) 2.2474(6), Fe(1)-C(1), 1.781(3), Fe(2)-C(2), 1.793(2); Fe(1)-Fe(2)-C(1) 72.02(9), Fe(1)-C(1)-O(1) 170.1(3).

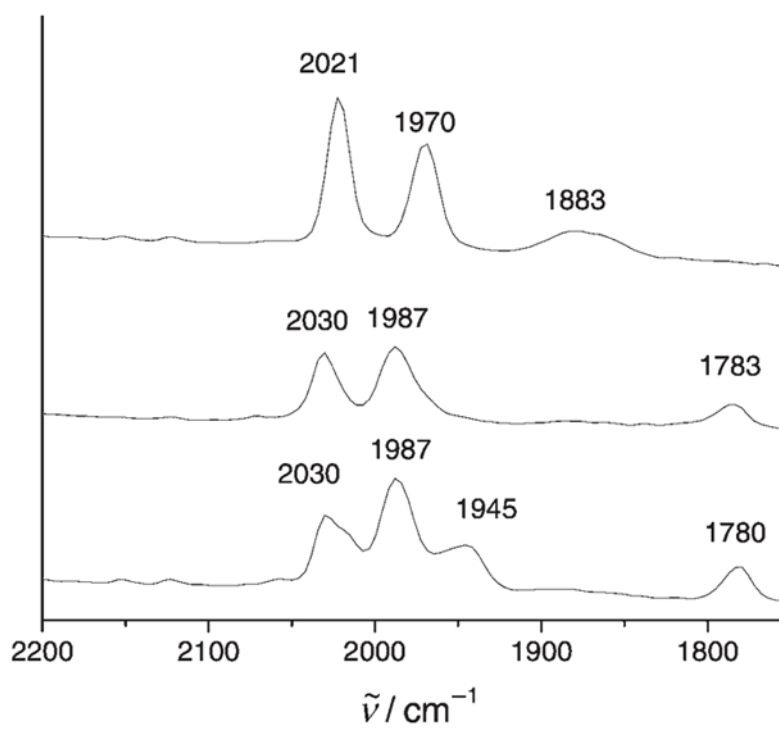
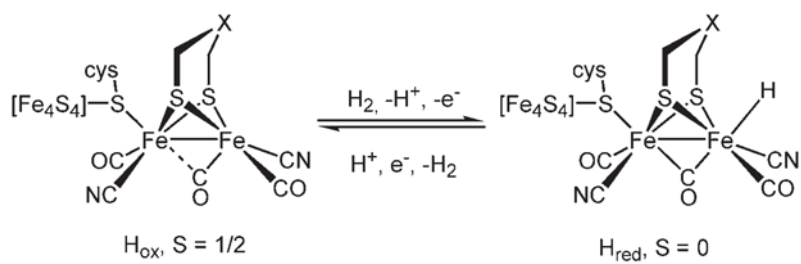
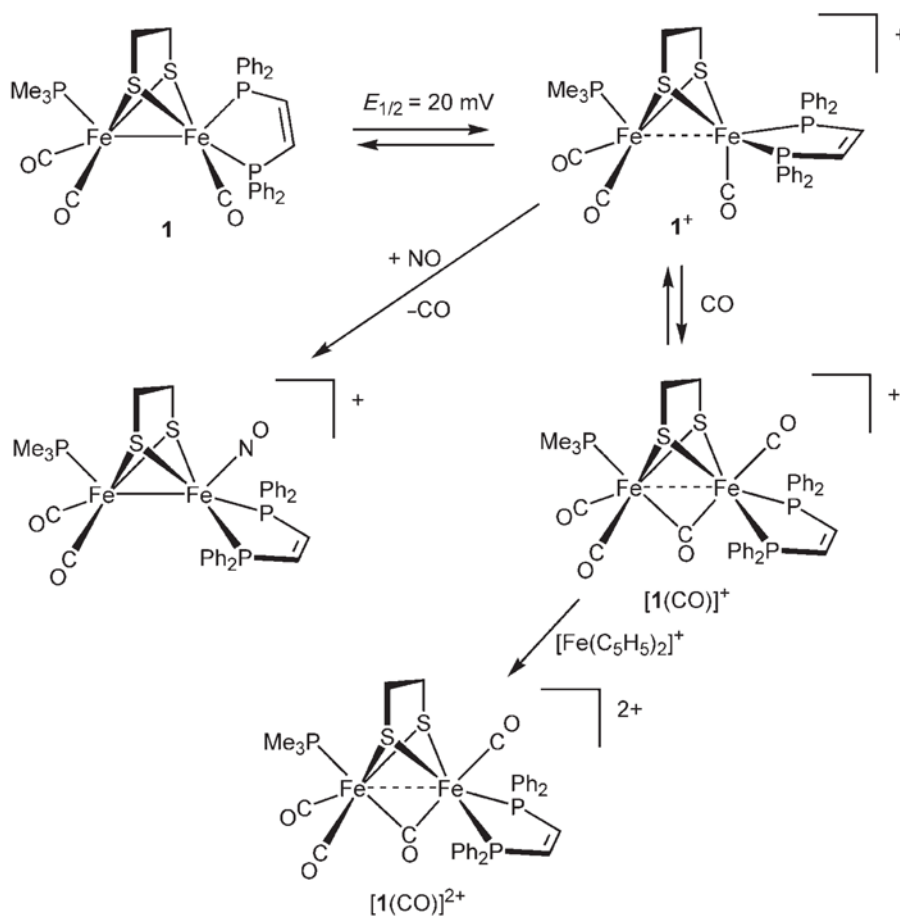


Figure 2. IR spectra ($-40\text{ }^{\circ}\text{C}$, CH_2Cl_2 solution) of $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]\text{BF}_4$ before CO treatment (top) and after treatment with ^{12}CO (middle) and ^{13}CO (bottom).

**Scheme 1.**

Two functional states of the active site of the [FeFe] hydrogenases.



Scheme 2.
 Synthesis and reactions of $[\text{Fe}_2(\text{S}_2\text{C}_2\text{H}_4)(\text{CO})_3(\text{PMe}_3)(\text{dppv})]^+$.

Table 1IR spectroscopic data for H_{ox} models and the enzyme.

Complex	$\tilde{\nu}_{\text{CO}}$ [cm ⁻¹]
[Fe ₂ (S ₂ C ₂ H ₄)(CO) ₃ (PMe ₃)(dppv)] ⁺ (I ⁺)	2021, 1970, 1883
[Fe ₂ (S ₂ C ₂ H ₄)(μ-CO)(CO) ₃ (PMe ₃)(dppv)] ⁺ ([I(CO)] ⁺)	2030, 1987, 1783
[Fe ₂ (S ₂ C ₂ H ₄)(μ-CO)(CO) ₃ (PMe ₃)(dppv)] ²⁺ ([I(CO)] ²⁺)	2063, 2028, 1939
H _{ox} (<i>D. desulfuricans</i>) ^[11]	1965, 1940, 1802
H _{ox} ^{CO} (<i>D. desulfuricans</i>) ^[11]	2016, 1972, 1963, 1811