Computational Investigation of [FeFe]-Hydrogenase Models: Characterization of Singly and Doubly Protonated Intermediates and Mechanistic Insights

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Supporting Information

ABSTRACT: The [FeFe]-hydrogenase enzymes catalyze hydrogen oxidation and production efficiently with binuclear Fe metal centers. Recently the bioinspired H₂-producing model system Fe₂(adt)(CO)₂(dpvp)₂ (adt=azadithiolate and dpvp=diphosphine) was synthesized and studied experimentally. In this system, the azadithiolate bridge facilitates the formation of a doubly protonated ammonium-hydride species through a proton relay. Herein computational methods are utilized to examine this system in the various oxidation states and protonation states along proposed mechanistic pathways for H₂ production. The calculated results agree well with the experimental data for the geometries, CO vibrational stretching frequencies, and reduction potentials. The calculations illustrate that the NH−HFe dihydrogen bonding distance in the doubly protonated species is highly sensitive to the effects of ion-pairing between the ammonium and BF₄⁻ counterions, which are present in the crystal structure, in that the inclusion of BF₄⁻ counterions leads to a significantly longer dihydrogen bond. The non-hydride Fe center was found to be the site of reduction for terminal hydride species and unsymmetric bridging hydride species, whereas the reduced symmetric bridging hydride species exhibited spin delocalization between the Fe centers. According to both experimental measurements and theoretical calculations of the relative pKₐ values, the Fe₄ center of the neutral species is more basic than the amine, and the bridging hydride species is more thermodynamically stable than the terminal hydride species. The calculations implicate a possible pathway for H₂ evolution that involves an intermediate with H₂ weakly bonded to one Fe, a short H₂ distance similar to the molecular bond length, the spin density delocalized over the two Fe centers, and a nearly symmetrically bridged CO ligand. Overall, this study illustrates the mechanistic roles of the ammonium-hydride interaction, flexibility of the bridging CO ligand, and intramolecular electron transfer between the Fe centers in the catalytic cycle. Such insights will assist in the design of more effective bioinspired catalysts for H₂ production.

1. INTRODUCTION

The design of H₂ oxidation and production electrocatalysts is critical for the development of alternative renewable energy technologies. The [FeFe]-hydrogenase enzymes catalyze these reactions effectively with binuclear Fe metal centers, as depicted in Figure 1.1−3 The detailed catalytic mechanism of these enzymes is still not completely understood. Fourier transform infrared spectroscopy (FTIR) and electron paramagnetic resonance (EPR) studies on the native enzyme have identified a mixed-valence oxidized state, H₁red, and a diamagnetic reduced state, H₀red.4−6 The H₁red state is well-characterized and features an obvious site for binding the H₂ substrate on the distal Fe center, denoted Fe₁ in Figure 1. The structure of the H₁red state is less clear because X-ray crystallography of biological systems cannot easily resolve hydrogen atoms. Although hypothesized for more than a decade,7,8 an azadithiolate bridgehead with an amine group pendant to the Fe metal center has only recently been confirmed experimentally.9,10 This recent insight is guiding current modeling and computational efforts. Relative to biophysical studies, an advantage of model systems is that hydride and dihydrogen species are readily observed by ¹H NMR and, in some cases, X-ray crystallography.11,12 Moreover, model systems are more computationally tractable, thereby providing additional structural and mechanistic insights.8,13−33

A variety of H₂-producing model systems inspired by [FeFe]-hydrogenases have been synthesized.34−38 Many of these models suffer from high overpotentials (i.e., negative reduction potentials) for hydrogen production. The recent H₂-producing models Fe₂(xdt)(CO)₂(dpvp)₂ (xdt = pdt, adt), depicted in Figure 2, rely on an electrode in place of the [Fe₄S₄] clusters that normally support electron transfer in the enzyme. Furthermore, in these models the CN and one of the CO ligands are replaced by diphosphine (dpvp) ligands.38 The presence of sterically crowded, electron-rich ligands on diiron carbonyl has been shown to stabilize the desired terminal hydride species.35,39 Through this approach, key hydride intermediates have been crystallographically character-
The most recent advance has revealed a key intermediate wherein the hydride is dihydrogen bonded to the protonated azadithiolate cofactor. 

This paper analyzes computationally the recent advances in the models and chemistry of the [FeFe]-hydrogenases. This paper has two components: benchmarking the computational methodology for these model systems and providing insights into the mechanism of H₂ production. The benchmarking provides the validation that is necessary to support the more hypothetical mechanistic predictions. In the first part of this paper, the computational methods are benchmarked by comparing experimental and theoretical structures, infrared (IR) vibrational frequencies of the CO groups, reduction potentials, and relative pKₐ values. The second part of this paper focuses on the mechanism for H₂ production. In particular, we examine these model systems in the various oxidation states and protonation states along proposed mechanistic pathways for H₂ production. Of particular interest, we aim to clarify the nature of the doubly protonated ammonium-hydride intermediate, which has been characterized crystallographically for this bimetallic system. Such doubly protonated intermediates have not been observed in bio-inspired monometallic Ni-based catalysts, although a mono-Fe catalyst in the doubly protonated state has very recently been characterized by DuBois and co-workers. We also present additional experimental data to validate the theoretical studies and to test predictions generated by the calculations.
An outline of this paper is as follows. In section II, we introduce the nomenclature for the species studied and describe the computational methods used to calculate the structures, CO vibrational frequencies, reduction potentials, and pKₐ values for these species. Section III presents the results and analysis, starting with the geometries and vibrational frequencies, followed by the reduction potentials and an analysis of the spin densities to determine the oxidation states of the metal centers. The second part of this section focuses on the protonation states and relative pKₐ values and presents an analysis of possible H₂ evolution mechanisms in the context of the experimental and computational data. Concluding remarks are presented in section IV.

II. METHODS

A. Defining the Nomenclature. The dion model systems can adopt numerous isomeric and geometric forms. Borrowing the nomenclature generally employed in enzymatic studies, the Fe center with the hydride is denoted distal (Fe₉) and the opposite Fe center is denoted proximal (Fe₅). Herein, we will abbreviate the [(Fe₉Fe₅)-

-acid) (CO₂)(dppv)] catalysts as [(FeFe)adt] for notational simplicity. Figure 2 depicts the electrocatalyst in the terminal hydride (H₂) form with xdt representing either a propanedithiol (pdth), [(FeFe)Fe⁺-pdt]⁻, or an azadithiolate (adt), [(FeFe)Fe⁺-adt]⁻. In this notation, the terminal hydride is always assumed to reside on the Feₗ center. Figure 3 depicts all of the protonation states of the [(FeFe)adt] species studied in this work. A similar scheme for the [(FeFe)pdt] species is available in the Supporting Information (Figure S17).

Although the terminal hydride (H₂) species are thermodynamically less stable than their associated bridging hydride (µH) isomers in model systems, experiments indicate that the terminal hydride species are much more catalytically active: they generate H₂ faster and at less negative potentials than their bridging hydride counterparts.35,38 The dependence of the reduction potential on the regiochemistry of the hydride remains unexplained but appears to be catalytically relevant. Whereas the [(FeFe)pdt] complex requires strong acids to form the terminal hydride species, [(FeFe)Fe⁺-pdt]⁻, the nearly isostructural [(FeFe)adt] complex can be protonated with weak acids due to the proposed relay activity of the azadithiolate.34 Specifically, the presence of the azadithiolate bridge permits the formation of the ammonium tautomer, [(FeFe)adt-H⁺], and subsequent intramolecular proton transfer to the Feₗ leads to the terminal hydride species, [(FeFe)Fe⁺-adt-H⁻]⁻ (Figure 3). Both [(FeFe)Fe⁺-adt]⁻ and [(FeFe)Fe⁺-pdt]⁻ convert to their respective bridging hydride isomers irreversibly at room temperature.35,38 Upon equilibration, two bridging hydride species form, sym-[µH-(FeFe)Fe⁺-adt]⁻ and asym-[µH-(FeFe)Fe⁺-adt]⁻, which differ in the orientation of the dppv ring on the Feₗ center relative to the dpdp ring on the Fe₉ center (Figure 3).

The adt-containing hydride species can undergo a second protonation with stronger acids, leading to the doubly protonated species, [(FeFe)Fe⁺-H₂]²⁻, (Figure 3). Again, [(FeFe)Fe⁺-dt-H⁻]⁻ isomerizes into two bridging hydrides, sym-[µH-(FeFe)Fe⁺-dt-H⁻]⁻ and asym-[µH-(FeFe)Fe⁺-dt-H⁻]⁻, albeit at a slower rate than the singly protonated analog.35,38 Although less thermodynamically stable than the bridging hydride species, the terminal hydride species, [(FeFe)Fe⁺-adt-H⁻]⁻, is poised for H₂ production due to the close proximity of the ammonium and Fe-hydride centers in the doubly protonated species.

B. Electronic Structure Methods. Density functional theory (DFT) calculations were performed to characterize the structural and energetic properties of the pertinent species in the catalytic scheme. All calculations were performed using the Gaussian 09 electronic structure program.45 For geometry optimizations, the starting geometries were obtained from the corresponding crystal structures, which are available for the [(FeFe)pdt]⁻, [(FeFe)pdta]⁻, asym-[µH-(FeFe)pdth]⁻, and asym-[µH-(FeFe)pdth]⁻ species,35 as well as the [(FeFe)Fe⁺]⁰ and [(FeFe)Fe⁺-adt]⁻ species.38 The starting geometries for species without crystal structures were obtained by manually altering the most closely related crystal structure. Optimizations in the gas phase and solution phase resulted in similar structures for several representative species, so gas phase optimizations were used herein for computational efficiency. A comparison of the structures optimized in the gas phase and solution phase for several representative species is available in the Supporting Information (Table S2).

The DFT calculations were performed using the B3P86 density functional47,48 with the Stuttgart pseudopotential and associated basis set of Preuss and co-workers (SDD) for the Fe centers,30 the 6-31G* basis set for the active hydrogens,30 the 6-31+G* basis set for the BF₄⁻ counters,31 and the 6-31G* basis set for all other atoms.32 To obtain the solvation free energies, we used the conductor-like polarizable continuum model (CPCM)34,35 with the Bondi atomic radii36 and included nonelectrostatic interactions, namely, the dispersion37,38 repulsion,39,40 and solvent correction.32,41 The solvation free energies were calculated in dichloromethane (CH₂Cl₂) to coincide with the experiments unless otherwise stated.

C. Calculation of Vibrational Frequencies, Reduction Potentials, and ΔpKₐ Values. The CO vibrational frequencies were calculated within the harmonic model and were scaled by a factor of 0.9850, as indicated by previous studies.33 The vibrational frequency shifts, ΔνCO, were calculated for the dashed pathways shown in Figure 3. For the [(FeFe)Fe⁺-adt]⁻ and [(FeFe)Fe⁺-adt-H⁻]⁻ species, the presence of the semibridging CO ligand allows for the assignment of two distinguishable CO stretching frequencies: the higher νCO corresponds to the terminal CO attached to the Fe₉ center, and the lower νCO corresponds to the semibridging CO. For all other species, both CO ligands are terminal, so their stretching frequencies are less separated.

In general, DFT does not consistently provide reliable absolute pKₐ's and reduction potentials because of limitations in the functionals, basis sets, and solvation models, as well as uncertainties in the free energies of the electron, proton, and electrode. As discussed previously,61 the calculation of pKₐ and reduction potentials relative to related reference systems with known experimental values has been shown to be more reliable because many of the systematic errors cancel. For this reason, we discuss only relative reduction potentials and pKₐ's in this paper. The structures and energies of all complexes discussed herein are provided in the Supporting Information.

The reaction free energies associated with reduction and deprotonation were calculated using the Born–Haber thermodynamic cycle. The reaction free energy for reduction, ΔG°(e⁻), was calculated using the expression

\[
\Delta G°(e⁻) = \Delta G°(s) + \Delta G°(Red) - \Delta G°(Ox)
\]

(1)

In this expression, \(\Delta G°(Red)\) and \(\Delta G°(Ox)\) are the solvation free energies of the reduced and oxidized species, respectively, and \(\Delta G°(s)\) is the gas phase reaction free energy calculated using the standard relation \(\Delta G°(s) = \Delta H°(s) - T \Delta S°\). A similar expression was used to calculate the reaction free energy for deprotonation, \(\Delta G°(H^+)\).

For reasons mentioned above, the reduction potentials were calculated relative to a related reference reaction for which the experimental value is known. This procedure accounts for systematic errors associated with the selected theoretical method and basis set and avoids the determination of the free energies of the electron and the electrode because these terms cancel. Detailed descriptions of this methodology can be found elsewhere.27,41–43 For our specific application, we used the following expression to calculate the reduction potentials:

\[
E° = E°_{\text{ref}} - \Delta G°(e⁻)/F
\]

(2)

Here, \(E°\) is the reduction potential of the [(FeFe)adt] species of interest, \(E°_{\text{ref}}\) is the experimentally measured reduction potential of the reference species, which is the [(FeFe)pdt] species in this work, \(\Delta G°(e⁻)\) is the calculated difference in reaction free energies (eq 1) for reduction of the species of interest and the reference, and \(F\) is the Faraday constant. All calculated and experimental reduction potentials are given in volts (V) relative to the ferrocene/ferrocinium (Fc'/Fc) couple.
The calculated reaction free energy for deprotonation, $\Delta G^{\circ}$, in CH$_3$CN, at 273 K, was reported to coincide with the reference potential. The cyclic voltammetry (CV) experiments were performed at 273 K, with other isomers of higher free energy provided in Figures S15 and S16, Supporting Information. The relative free energies of these species and energetic information on all systems studied herein are provided in the Supporting Information. The relative free energies are defined as the difference between the p$_K$ values for two specified states of the [Fe(Fe$^{II}$)adt] complex. The reported p$_K$ values were calculated in CH$_3$CN to coincide with experimental conditions and in acetonitrile (CH$_3$CN) to coincide with the reference p$_K$ values used in the interpretation of the experimental values because a pH scale is not well established for CH$_3$Cl$_2$.

### III. RESULTS AND DISCUSSION

#### A. Geometries, Free Energies, and Vibrational Frequencies

We optimized the geometries of the various species discussed above and compared the structures and key vibrational frequencies to available experimental data. The optimized geometries are in reasonable agreement with the X-ray crystal structures. Table 1 provides a comparison of the most relevant bond lengths for the various species. Structural and vibrational information on all systems studied herein are provided in the Supporting Information. The relative free energies of the species depicted in Figure 3 are provided in Table 2. Moreover, the relative free energies of these species and other isomers of higher free energy are provided in Figures S15 and S16, Supporting Information.

| species                      | Fe$_{8+}$−Fe$_{8-}$ | Fe$_{8+}$−CO | Fe$_{8+}$−CO | Fe$_{8+}$−H | Fe$_{8+}$−H |
|------------------------------|---------------------|--------------|--------------|-------------|-------------|
| [(Fe$^{III}$Fe$^{III}$)adt]$^2$ | 2.60 ± 0.03         | 1.74 ± 0.03  | 1.75 ± 0.03  | g           | g           |
| [(Fe$^{III}$Fe$^{III}$)adt]$^+$ | 2.59 ± 0.03         | 1.75 ± 0.03  | 1.79 ± 0.03  | g           | g           |
| unsym-[μ-Fe(Fe$^{III}$)adt]$^2$ | 2.66 ± 0.03         | 1.78 ± 0.03  | 1.74 ± 0.03  | 1.69 ± 0.03 | 1.65 ± 0.03 |
| unsym-[μ-Fe(Fe$^{III}$)adt]$^+$ | 2.80 ± 0.03         | 1.75 ± 0.03  | 1.78 ± 0.03  | 1.82 ± 0.03 | 1.61 ± 0.03 |
| [Fe$^{III}$adt]$^2$           | 2.60 ± 0.03         | 1.74 ± 0.03  | 1.75 ± 0.03  | g           | g           |
| [H-[Fe$^{III}$Fe$^{III}$]adt-H$^+$] | 2.62 ± 0.03         | 1.72 ± 0.03  | 1.79 ± 0.03  | g           | 1.44 ± 1.53 |

Values given in Å. Experimental data from ref 35. The optimized geometry for the doubly protonated species, [H-[Fe$^{III}$Fe$^{III}$]adt-H$^+$], exhibited one key difference from the crystal structure, namely, the dihydrogen distance NH···HFe. This dihydrogen distance was $d_{NH} = 1.88$ Å in the crystal structure and $d_{NH} = 1.90$ Å in the optimized geometry. Thus, DFT leads to a significantly shorter dihydrogen distance that corresponds to a stronger dihydrogen bond.45

### Table 2. Calculated Relative Free Energies ($\Delta G^\circ$) of Protonated Species

The optimized geometries of the various species discussed above and compared the structures and key vibrational frequencies to available experimental data. The optimized geometries are in reasonable agreement with the X-ray crystal structures. Table 1 provides a comparison of the most relevant bond lengths for the various species. Structural and vibrational information on all systems studied herein are provided in the Supporting Information. The relative free energies of the species depicted in Figure 3 are provided in Table 2. Moreover, the relative free energies of these species and other isomers of higher free energy are provided in Figures S15 and S16, Supporting Information.

| species                      | $\Delta G^\circ$ |
|------------------------------|-----------------|
| [(Fe$^{III}$Fe$^{III}$)adt]$^2$ | 0.00            |
| [(Fe$^{III}$Fe$^{III}$)adt]$^+$ | $-279.32$       |
| [H-[Fe$^{III}$Fe$^{III}$]adt-H$^+$] | $-286.09$      |
| unsym-[μ-Fe(Fe$^{III}$)adt]$^2$ | $-296.64$       |
| unsym-[μ-Fe(Fe$^{III}$)adt]$^+$ | $-294.70$       |
| [H-[Fe$^{III}$Fe$^{III}$]adt-H$^+$] | $-553.02$      |
| unsym-[μ-Fe(Fe$^{III}$)adt-H$^+$] | $-564.82$      |
| unsym-[μ-Fe(Fe$^{III}$)adt-H$^+$] | $-561.16$      |

Values given in kcal/mol relative to the unprotonated species, [(Fe$^{III}$Fe$^{III}$)adt]$^2$, in CH$_3$CN, at 298.15 K. The free energy of a solvated proton should be included to obtain free energies relevant to the protonation reactions.
of the experimentally measured values. This level of agreement provides validation for the structures of species for which crystal structures are not available. Typically DFT calculations are more reliable for changes in frequencies than for absolute frequencies; a comparison between the calculated and experimental absolute frequencies is provided in Table S4, Supporting Information. For the present study, the previously reported spectroscopic studies were repeated using the acid [H(OEt)_2]BARF_4 to eliminate the possibility of ion pairing arising from the coordination of BF_4^- when using HBF_4·Et_2O, which has been shown to participate in hydrogen-bonding interactions, particularly in complexes with protonated adt ligands. The agreement between calculated and experimental frequencies is better for the BARF_4^- salts; these spectra are provided in the Supporting Information (Figures S6 and S7). The Δν_CO values reflect the protonation sites, as indicated by both experimental measurements and theoretical calculations. The Δν_CO values associated with N-protonation are typically characterized by CO frequency increases of ~20 cm\(^{-1}\).The experimental and calculated Δν_CO values associated with N-protonation to form either the singly or doubly protonated species (P1, P4, and P5 protonations) exhibit this shift. While N-protonation is associated with a relatively small ν_CO shift, formation of the terminal and bridging hydrides (P2 and P3 protonations, respectively) is associated with much higher shifts of ~70 cm\(^{-1}\). In both cases, two well-resolved bands are observed in the spectra, but the bands are much more energetically separated for the terminal hydride species than for the bridging hydride species. The band at lower frequencies in the terminal hydride species is assigned to the semibridging CO, which exhibits a smaller ν_CO shift of ~40 cm\(^{-1}\). Our calculated Δν_CO values for the protonations leading to the terminal and bridging hydrides (P2 and P3 protonations, respectively) demonstrate this trend and agree well with the experimental values (Table 4). An analogous figure and table for the [(FeFe)pdt] complexes is provided in the Supporting Information (Figure S17 and Table S1).

### B. Reduction Potentials

The calculated reduction potentials for the species in CH_2Cl_2 are presented in Table 5. Because the [(FeFe)pdt] species are used as the reference systems, these reduction potentials agree exactly with experiment by construction, and all other reduction potentials are calculated relative to these values. The agreement between theory and experiment for the [(FeFe)adt] species is reasonable for the singly protonated species with errors of ~0.05 V vs Fe^0/Fc^- in CH_2Cl_2. Additional calculated reduction potentials are provided in the Supporting Information (Table SS). A detailed analysis of the metal oxidation states of the reduced species in terms of the spin densities is provided in the next subsection.

### Table 3. Selected Bond Lengths from DFT Calculations and X-ray Structures for Doubly Protonated Species Optimized with and without BF_4^- Anions

|                | Fe-C-Fe | Fe-C-H | N-H | H-H |
|----------------|---------|--------|-----|-----|
| exp^d          | 2.62    | 1.44   | 1.00| 1.88|
| no BF_4^-      | 2.65    | 1.53   | 1.07| 1.40|
| solution^c     | 2.61    | 1.51   | 1.04| 1.55|
| 1:BF_4^-       | 2.62    | 1.51   | 1.04| 1.65|
| 2:BF_4^-       | 2.59    | 1.50   | 1.04| 2.04|

^dValues given in Å. All optimizations were conducted in the gas phase unless stated otherwise. ^cExperimental data from ref 38. ^dThis structure was optimized in solution (CH_2Cl_2) using C-PCM without any BF_4^- counterions.

### Table 4. Experimental and Calculated Δν_CO Values upon Protonation

| reaction | exp^e | calc^d |
|----------|-------|--------|
| P1       | 22, 22| 31, 30 |
| P2^c     | 78, 46| 86, 37 |
| P3       | 82, 79| 89, 77 |
| P4^c     | 24, 21| 27, 34 |
| P5       | 19, 17| 29, 29 |

^eValues given in cm\(^{-1}\). ^cThe P1, P2, P3, P4, and P5 protonation reactions are defined in Figure 3. ^dExperimental data from ref 38. ^fFrequencies scaled by a factor of 0.9850. The second Δν_CO value is assigned to the semibridging CO.

### Table 5. Experimental and Calculated Reduction Potentials

| species       | E^c [(FeFe)]^+/0 | E^c [H-(FeFe)]^+/0 | E^c [H-(FeFe)]^+/0 | E^c ionp [H-(FeFe)]^+/0 |
|---------------|------------------|--------------------|--------------------|-------------------------|
| [(FeFe)pdt]^b | exp^f            | -0.94              | -1.70^d            | -1.80                   |
|               | calc             | -0.94              | -1.70              | -1.80^d                 |
| [(FeFe)adt]   | exp^f            | -0.76              | -1.66^e            | -1.79                   |
|               | calc             | -0.84              | -1.69              | -1.77^h                 |

^fValues given in volts vs Fe^0/Fc^- in CH_2Cl_2. Experimental E_1/2 values given unless otherwise indicated. ^b[(FeFe)pdt] reactions were used as the reference reactions, so the calculated and experimental values agree by construction. ^cExperimental data from ref 79. ^dQuasi-reversible reaction, so E_p is reported. ^eE^c = -1.82 V vs Fe^0/Fc^- in CH_2Cl_2 if calculated using the symmetric bridging form. ^fExperimental data from ref 38. ^gIrreversible reaction, so E_p is reported. ^hE^c = -1.83 V vs Fe^0/Fc^- in CH_2Cl_2 if calculated using the symmetric bridging form.
Due to difficulties in determining a suitable reference system for the doubly protonated species, we calculated the difference between the reduction potentials for the doubly and singly protonated species ($\Delta E_{\text{prot}}$). Using this formulation, we calculated $\Delta E_{\text{prot}} = 0.59$ vs Fe$^3$/Fe$^2$ in CH$_2$Cl$_2$. As expected from basic electrostatic arguments, the doubly protonated species has a less negative reduction potential than the singly protonated species. The experimentally measured difference in these reduction potentials was 0.39 V vs Fe$^3$/Fe$^2$ in CH$_2$Cl$_2$.

As discussed above, this error could be due to the neglect of BF$_4^-$ in the calculations. Note that BF$_4^-$ ions were present in the electrochemical measurements for the doubly protonated species but not for the singly protonated species. Furthermore, the effects of ion pairing on reduction potentials are known to be pronounced in solvents of low dielectric constants, such as CH$_2$Cl$_2$.

Thus, the difference in the counterions present for the electrochemical experiments of the singly and doubly protonated species could lead to discrepancies in the comparison between calculated and experimental results. Note that the experimentally measured reduction potentials for the terminal hydride species are for quasireversible couples, which could introduce additional discrepancies.

C. Analysis of Metal Oxidation States.

For species with an unpaired electron, we analyzed the spin densities to determine the localization of the unpaired electron. The spin densities for the reduced species are presented in Table 6. For the reduced terminal hydride species, [$\text{H}-(\text{Fe}^3\text{Fe}^3)\text{adt}$]$\text{p}^0$, the unpaired spin density is localized entirely on the Fe$_p$ center, suggesting that the Fe$_p$ center is reduced. This localization on the Fe$_p$ center is similar for the reduced terminal hydride species, [$\text{H}-(\text{Fe}^3\text{Fe}^3)\text{pdt}$]$\text{p}^0$, which is produced at a similar potential as the [$\text{H}-(\text{Fe}^3\text{Fe}^3)\text{adt}$]$\text{p}^0$ species, indicating that the dithiolate is not a major influence on the redox behavior for the terminal hydride species. The spin densities pertaining to the [(FeFe)$_2$] complexes are provided in the Supporting Information (Table S6).

Previous studies also examined the metal oxidation states upon reduction of [$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ by analyzing the spin density with the BP86 functional and EPR spectra of the mixed-valence species.

These studies showed that reduction of sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ results in a species with the unpaired electron delocalized between the Fe$_p$ and Fe$_d$ centers, sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^0$. However, reduction of unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ resulted in a species with the unpaired electron localized on the Fe$_p$ center, unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^0$. Our calculations revealed a similar trend with the bridging hydride species of the singly and doubly protonated [(FeFe)$_2$] (Table 6), although several important differences were observed.

In the singly protonated symmetric and unsymmetric [(FeFe)$_2$] bridging hydride species, sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$ and unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$, the orientations of the dppv ligands on the two Fe centers dictate the overall symmetry of the system, as depicted in Figure 3. Furthermore, the hydride is located symmetrically between the two Fe centers in both isomers for the oxidized state. These distances are reported in Figure 5. Upon reduction, the bridging hydride is perturbed from this symmetric position. In the reduced unsymmetric bridging hydride species, the hydride is more closely bound to Fe$_d$ ($d_{\text{Fe}-\text{H}} = 1.58$ Å) than to Fe$_p$ ($d_{\text{Fe}-\text{H}} = 2.05$ Å) and resembles a terminal hydride. In the reduced symmetric bridging hydride species, the hydride is more symmetrically bound to the two iron centers ($d_{\text{Fe}-\text{H}} = 1.60$ Å for Fe$_p$ and $d_{\text{Fe}-\text{H}} = 1.77$ Å for Fe$_d$). The observation that the reduction of sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$ maintains a more symmetric bridging hydride is consistent with the observation that the spin density is somewhat delocalized between the two Fe centers. In contrast, reduction of unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$ leads to a much more asymmetric bridged hydride, and the spin density is localized on Fe$_p$ which does not have a bound hydride. Thus, unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ also involves motion of the bridged hydride toward the Fe$_d$ site to resemble a terminal hydride. These observations are consistent with the observation that the terminal hydride species is reduced more easily (i.e., at a slightly less negative potential) than the unsymmetric bridging hydride species (Table S5).

The presence of the amine group in the azadithiolate bridgehead affects the degree of asymmetry observed upon reduction of the symmetric bridging hydride species. Although the bridging hydride is more symmetric in the sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$ species than in the unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$ species, more asymmetry is exhibited in the sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ than in the analogous sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ species. In the previous study of [(FeFe)$_2$] bridging hydride species, reduction of sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$ preserves the symmetry of the hydride position to a higher degree, with $d_{\text{Fe}-\text{H}} = 1.68$ Å and $d_{\text{Fe}-\text{H}} = 1.70$ Å for the Fe$_p$ and Fe$_d$ centers, respectively. We have confirmed these observations using the level of theory described within the present paper and various other basis sets. These results are given in the Supporting Information (Table S7). Moreover, these nearly symmetric Fe···H bond lengths are associated with nearly equal spin densities on the two Fe centers. As shown in Figure 5 and Table 6, the reduced symmetric protonated [(FeFe)$_2$] system, sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{pdt}$]$\text{p}^+$, exhibits more asymmetry in these Fe···H bond lengths and unequal delocalized spin densities on the two Fe centers.

The reduction of the doubly protonated bridging hydride species, unsym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$ and sym-[$\mu\text{H}-(\text{Fe}^4\text{Fe}^6)\text{adt}$]$\text{p}^+$, follows a similar trend but displays a slightly smaller degree of delocalization of the spin density, as shown in Table 6. According to the distances given in Figure 5, the asymmetry of the bridging hydride is slightly more pronounced in both the symmetric and unsymmetric forms for the doubly protonated species. Thus, reduction is expected to occur primarily at the nonhydride Fe$_p$ center, as supported by the unpaired spin densities given in Table 6. This pattern for the electron localization is also seen in doubly protonated terminal hydride species, which will be discussed below.

D. Analysis of the Protonation Scheme and $\Delta \rho_K$.

Previous experiments on the [(FeFe)$_2$] system estimated a small difference in the $p_K$ of the first and second protonation steps ($\Delta \rho_K \approx -2$); however, our calculated values indicated...
much larger differences, as seen from $\Delta pK_a(P4 - P2)$ in Table 7. This discrepancy between experiment and theory prompted a reinvestigation of the acid-base chemistry of the [(FeFe)adt] species. The $pK_a$ values can be estimated by NMR measurements because each protonated species displays a unique $^{31}$P NMR spectrum. The experimental details and spectra are provided in the Supporting Information (Figures S12 and S13). According to these experiments, the protonation reactions leading to the formation of [(FeFe)adt-H]$, ([H-(FeFe$^{III}$)-adt]$, and ([H-(FeFe$^{III}$)adt-H]$^{2+}$, defined as P1, P2, and P4 in Figure 3, correspond to $pK_a$ values of $>$14.2, $\sim$15.5, and $\sim$6, respectively.

For reasons discussed in the Methods section, we calculated only the relative $pK_a$ values for these species. This procedure accounts for systematic errors associated with the selected theoretical method and avoids the determination of the free energy of the solvated proton because this term cancels. Note that the experimentally measured values are only qualitatively meaningful because the experiments were performed in CH$_2$Cl$_2$, which does not have a well-defined $pK_a$ scale, and the reference $pK_a$ values of the acids pertain to CH$_3$CN. As a result, we calculated the relative $pK_a$ values in both CH$_2$Cl$_2$ and CH$_3$CN. Additionally, the effects of homoconjugation in these experiments may distort the apparent $pK_a$ measured. As discussed above in the context of comparing the crystal structure and optimized geometries, the impact of ion pairing is significant for the doubly protonated species. Furthermore, it has been shown experimentally that ion pairing between the BF$_4^-$ counterion and the ammonium center can shift the equilibrium of the singly protonated species toward [(FeFe$^{III}$)-adt-H]$^{+}$.

The experimental and calculated $\Delta pK_a$ values for these species are given in Table 7. The experimental $\Delta pK_a(P2 - P1)$ value indicates that the Fe$_{ed}$ site is more basic than the amine by at least $\sim$1.3 $pK_a$ units; however, the amine is more readily protonated than the stereochemically crowded Fe site. The greater basicity of the Fe$_{ed}$ site than the amine is corroborated by our calculated $\Delta pK_a(P2 - P1)$ value of $\sim$6 in CH$_2$Cl$_2$. The large, negative $\Delta pK_a(P4 - P2)$ value measured experimentally indicates that N-protonation of [(H-(FeFe$^{III}$)adt-H]$^{+}$ to form [(H-(FeFe$^{III}$)adt-H]$^{2+}$ requires much stronger acids, as supported by our calculated large, negative $\Delta pK_a(P4 - P2)$. Note that this experimentally measured value of $\Delta pK_a(P4 - P2)$ is significantly more negative than the previously measured value.

Again, it is worth noting that the presence of the BF$_4^-$ ions in the experiments may contribute to the remaining discrepancy between theory and experiment. Moreover, the theoretical calculation of $pK_a$ differences for species with different charges (i.e., $+2$ and $+1$ for the doubly and singly protonated species) is more challenging. Turning our attention to the bridging hydride isomers, previous experiments have suggested that the conversion to the bridging hydride isomers is...
irreversible, and the bridging hydride is estimated to be at least \( \sim 2pK_a \) units less acidic than the terminal hydride.\(^{35,38} \) This observation is supported by the large, positive calculated \( \Delta pK_a (P3-P2) \) value and the thermodynamic stability of the bridging hydride isomers. These \( \Delta pK_a \) trends are reproducible using different functionals, as indicated by additional data provided in the Supporting Information (Table S8).

E. Analysis of the \( \text{H}_2 \) Evolution Mechanism. The proposed mechanisms for hydrogen evolution catalyzed by the \( ([\text{FeFe}]) \) system for weak and strong acids are depicted in Figure 6. Initially, the amine group on \( ([\text{FeIFeI}])_0 \) is protonated to form the ammonium tautomer, \( ([\text{FeIFeI}])_{-H}^+ \). An intramolecular proton transfer occurs from the N to the Fe to form the terminal hydride, \( ([\text{H}-(\text{FeIFeI})_{-H}])^+ \). For weak acids, the terminal hydride species, \( ([\text{H}-(\text{FeIFeI})_{-H}])^+ \), is reduced prior to subsequent protonation and reduction to evolve \( \text{H}_2 \). This pathway is shown in dotted lines in Figure 6.

For stronger acids, the intramolecular proton transfer is followed by another protonation at the amine group to generate \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-H}^+ \). Reduction of this doubly protonated species then evolves \( \text{H}_2 \). A possible mechanism for this process is indicated with solid lines on the right side of Figure 6. The values for the spin densities and bond distances for the species associated with this pathway are given in Table 8.

Our calculations indicate that reduction of \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-H}^+ \) leads to the mixed-valence complex, \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-CO}^+ \). The spin densities and bond distances of this species are given in Table 8. This mixed-valence species is characterized by the unpaired electron localized on the Fe center, which is in agreement with the reduction scheme exhibited by the \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-CO}^+ \) and \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-CO}^+ \) species discussed previously. The \( \text{NH} \cdots \text{HFe} \) distance is shorter in \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-CO}^+ \) (\( d_{\text{H} \cdots \text{H}} = 1.30 \) Å) than in \( ([\text{H}-(\text{FeIFeI})_{-H}])_{-CO}^+ \) (\( d_{\text{H} \cdots \text{H}} = 1.40 \) Å) but is still larger than the distance in molecular \( \text{H}_2 \) (\( d_{\text{H} \cdots \text{H}} = 0.74 \) Å). Although we were unable to locate a minimum-energy species with \( \text{H}_2 \) weakly bound to an Fe center, we found another type of \( \text{H}_2 \) adduct intermediate with the unpaired electron delocalized between the Fe and Fe centers. This \( \text{H}_2 \) adduct, \( ([\text{H}-(\text{FeFe})_{-H}])_{-CO}^+ \), is higher in free energy than the mixed-valence doubly protonated species, \( ([\text{H}-(\text{FeFe})_{-H}])_{-CO}^+ \), by 5.82 kcal/mol but has several
features that are potentially catalytically relevant, as will be discussed below. Note that previous theoretical studies on small models of the [FeFe]-hydrogenase active site found that reduction of a doubly protonated Fe\textsubscript{p}(II)Fe\textsubscript{d}(II) species could lead to the formation of a stable mixed-valence H\textsubscript{2} adduct intermediate, Fe\textsubscript{p}(I)Fe\textsubscript{d}(II), where the Fe\textsubscript{p} center is the site of reduction and the H\textsubscript{2} ligand is loosely bound to the Fe\textsubscript{d}(II) center.\textsuperscript{8,19} These mixed-valence intermediates are similar to the \([\text{H}\text{-Fe(Fe)}^{II}\text{-Fe}^{III}]\text{-adt}\text{-H}^{-}\) species found herein; however, the \([\text{H}_{2}\text{-Fe}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) species was not found in these previous studies.

In contrast to the \([\text{H}\text{-Fe(Fe)}^{III}\text{-Fe}^{III}\text{-ldt}-\text{H}]^{-}\) species, the \([\text{H}_{2}\text{-Fe}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) species features a much shorter NH···HFe distance \((d_{\text{H},\text{H}} = 0.79 \text{ Å})\), suggesting an activated H\textsubscript{2} molecule. In conjunction with the activated H\textsubscript{2} bond distance, the average distance between each hydrogen and the Fe\textsubscript{d} center is elongated \((d_{\text{H},\text{Fe}} = 1.75 \text{ Å})\), suggesting that the H\textsubscript{2} ligand is weakly bound to the Fe\textsubscript{d} center and poised for release. Another important structural feature is that unlike all terminal hydride species reported in the present paper, the semibridging CO ligand in this H\textsubscript{2} adduct is nearly symmetrically bridged between the Fe\textsubscript{p} and Fe\textsubscript{d} centers, where \(d_{\text{Fe}\text{-CO}} = 2.06 \text{ and } 1.89 \text{ Å}\), respectively. The Fe\textsubscript{p}···Fe\textsubscript{d} distance contracts \((d_{\text{Fe}\text{-Fe}} = 2.69 \text{ Å})\) to accommodate this bridging interaction. This structural property is reminiscent of the enzyme’s H\textsubscript{ox} state, which features a nearly symmetrically bridged CO ligand (Figure 1). Moreover, the spin density is now delocalized between the Fe\textsubscript{p} and Fe\textsubscript{d} center, 0.43 and 0.45, respectively, warranting the \([\text{H}_{2}\text{-Fe}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) assignment. This delocalization of the spin density suggests the possibility for intramolecular electron transfer to occur between the Fe\textsubscript{p} and Fe\textsubscript{d} centers concomitant with formation of a shorter H\textsubscript{2} bond. Note that the proposed mechanism in Figure 6 is similar to mechanisms proposed previously for [FeFe]-hydrogenases in terms of the reduction and protonation steps.\textsuperscript{8,13–15,21} Our objective is to characterize the proposed intermediates and to analyze aspects such as dihydrogen bonding and electron delocalization or localization with respect to the metal centers.

Release of H\textsubscript{2} from \([\text{H}_{2}\text{-Fe(Fe)}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) would generate another mixed-valence state, the \([\text{Fe}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) species shown in Figure 6. This mixed-valence species is closely related to the H\textsubscript{ox} state of the enzyme shown in Figure 1. Interestingly, the spin densities for this species, which are given in Table 8, indicate Fe oxidation states that are opposite to the various other mixed-valence species discussed in this paper. Whereas the spin density was localized on the Fe\textsubscript{p} center for the other purely mixed-valence species, such as \([\text{H}(\text{Fe}^{III}\text{-Fe})^{II}\text{-ldt}]^{-}\) and \([\text{H}\text{-Fe(Fe)}^{III}\text{-Fe}^{III}\text{-ldt}-\text{H}]^{-}\), this H\textsubscript{ox}-like species has the spin density entirely localized on the Fe\textsubscript{d} center, suggesting that the Fe\textsubscript{d} center is now more reduced than the Fe\textsubscript{p} center. Upon formation of this \([\text{Fe}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) species, the bridging CO ligand returns to the original asymmetric semibridging position. This analysis of the mechanism points to the importance of the bridging CO ligand, which seemingly behaves as a lever and indicator for intramolecular electron transfer between the Fe centers. Moreover, there is 0.16 spin density localized on the symmetric bridging CO ligand in the \([\text{H}_{2}\text{-Fe(Fe)}^{III}\text{-Fe}^{III}\text{-ldt}]^{-}\) species, suggesting that it may be even more involved in the electron transfer process.

IV. CONCLUDING REMARKS

In this paper, we investigated a proton reduction catalyst, \([\text{(FeFe)ldt}]^{-}\), which is modeled after the [FeFe]-hydrogenase enzyme. This model is characterized by incorporation of the azadiithiolate bridge, which facilitates the formation of a doubly protonated species through a proton relay. The calculated results agree well with the experimental data for the geometries, CO vibrational stretching frequencies, and reduction potentials for the systems studied. This agreement provides validation for the computational methods. The calculations illustrate that the NH···HFe dihydrogen bonding distance in the doubly protonated species is highly sensitive to the effects of ion-pairing between the ammonium and BF\textsubscript{4}⁻ counterions, which are present in the crystal structure. Specifically, the inclusion of BF\textsubscript{4}⁻ counterions leads to a significantly longer dihydrogen bond. Comparable weak interactions with the protein backbone might be expected to influence the H···H bonding in the enzyme. Analyses of spin densities provide insight into the oxidation states of the metal centers for the reduced singly and doubly protonated species. The non-hydride Fe center (Fe\textsubscript{p}) was found to be the site of reduction for terminal hydride species and for unsymmetric bridging hydride species. In contrast, the reduced symmetric bridging hydride species exhibited a significant degree of spin delocalization between the Fe centers, although these species exhibited more asymmetry than the analogous [FeFe]pdt species. These differences in the degree of spin localization, as well as the movement of the hydride upon reduction of the unsymmetric bridging species, may be related to the experimental observation that the terminal hydride species are reduced at less negative potentials than their bridging hydride isomers.\textsuperscript{35,41,78} This analysis suggests that the bridging hydrides may be considered to be quasi-terminal hydrides for the unsymmetric species.

A combined experimental and theoretical study of the relative pK\textsubscript{a} values for the various species in the catalytic cycle provides further insights. The Fe\textsubscript{d} site was found to be more basic than the amine, although the amine is more readily protonated. Moreover, the bridging hydride species was found to be more thermodynamically stable than the terminal hydride species. These observations are consistent with the initial protonation of the amine, followed by intramolecular proton transfer to the Fe\textsubscript{d} site to produce a terminal hydride species, followed by isomerization to the bridging hydride species at room temperature but not at low temperatures. In terms of forming the doubly protonated species, the amine site is significantly less basic for the terminal hydride species than for the unprotonated species. Both the experimental and theoretical data indicate that a stronger acid is required for this second protonation.

In addition, these calculations implicate a possible pathway for H\textsubscript{2} evolution that involves an intermediate with H\textsubscript{2} weakly bonded to one Fe, a short H\textsubscript{2} distance similar to the molecular bond length, the spin density delocalized over the two Fe centers, and a nearly symmetrically bridged CO ligand. The short H\textsubscript{2} distance implies that the Fe···H\textsubscript{2} bonding is relatively weak and that the product H\textsubscript{2} is poised for release. Upon H\textsubscript{2} release, the mixed-valence species produced is closely related to the H\textsubscript{ox} state of the enzyme. The key features of this proposed mechanism highlight the roles of the ammonium-hydride interaction, flexibility of the bridging CO ligand, and intramolecular electron transfer between the Fe centers in the catalytic cycle. While these bioinspired models are effective catalysts for H\textsubscript{2} production, the challenge of designing molecular electrocatalysts that can perform with weaker acids and lower overpotentials remains.\textsuperscript{1} Further investigation of the
effects of ligand substitution at the Fe centers will help guide the design of more effective H₂-producing catalysts.

**ASSOCIATED CONTENT**

 Supporting Information

 Details of experimental methods, ³¹P NMR, ¹H NMR, and FT-IR spectra of the species studied, experimental measurement of pKₐ relative free energies of all protonated [(FeFe)adt] species, protonation scheme, ΔνCO and spin densities of [(FeFe)pdt] species, comparison of crystal structures and DFT optimized structures, expanded version of Table S, ΔpKₐ values calculated using different levels of theory and solvents, and coordinates of optimized structures. This material is available free of charge via the Internet at http://pubs.acs.org.

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**REFERENCES**

(1) Fontecilla-Camps, J. C.; Volbeda, A.; Cavazza, C.; Nicolet, Y. Chem. Rev. 2007, 107, 4273.
(2) Tard, C.; Pickett, C. J. Chem. Rev. 2009, 109, 2245.
(3) Lubitz, W.; Ogata, H.; Rüdiger, O.; Reijerse, E. Chem. Rev. 2014, 114, 4081.
(4) Albracht, S. J.; Roseboom, W.; Hatchikian, E. C. J. Biol. Inorg. Chem. 2006, 11, 88.
(5) De Lacey, A. L.; Fernández, V. M.; Rousseau, M.; Cammack, R. Chem. Rev. 2007, 107, 4304.
(6) Lubitz, W.; Reijerse, E.; van Gastel, M. Chem. Rev. 2007, 107, 4331.
(7) Nicolet, Y.; de Lacey, A. L.; Vernède, X.; Fernández, V. M.; Hatchikian, E. C.; Fontecilla-Camps, J. C. J. Am. Chem. Soc. 2001, 123, 1596.
(8) Fan, H.-J.; Hall, M. B. J. Am. Chem. Soc. 2001, 123, 3828.
(9) Berggren, G.; Adamska, A.; Lambertz, C.; Simmons, T. R.; Esselborn, J.; Atta, M.; Gambarello, S.; Mouesca, J. M.; Reijerse, E.; Lubitz, W.; Happe, T.; Artero, V.; Fontecave, M. Nature 2013, 499, 66.
(10) Esselborn, J.; Lambertz, C.; Adamska-Venkatesh, A.; Simmons, T.; Berggren, G.; Noth, J.; Siebel, J.; Hemscheimer, A.; Artero, V.; Reijerse, E.; Fontecave, M.; Lubitz, W.; Happe, T. Nat. Chem. Biol. 2013, 9, 607.
(11) Ezzaheb, S.; Capon, J.-F.; Gloaguen, F.; Pélisson, F. Y.; Schollhammer, P.; Talatín, J.; Pichon, R.; Kervarec, A. Inorg. Chem. 2007, 46, 3426.
(12) Zaffaroni, R.; Rauchfuss, T. B.; Gray, D. L.; De Gioia, L.; Zampella, G. J. Am. Chem. Soc. 2012, 134, 19260.
(13) Cao, Z.; Hall, M. B. J. Am. Chem. Soc. 2001, 123, 3734.
(14) Liu, Z.-P.; Hu, P. J. Chem. Phys. 2002, 117, 8177.
(15) Liu, Z.-P.; Hu, P. J. Chem. Phys. 2002, 117, 8177.
(16) Daresbourg, M. Y.; Lyon, E. J.; Zhao, X.; Georgakakia, I. P. Proc. Natl. Acad. Sci. U.S.A. 2003, 100, 3683.
(17) Wilson, A. D.; Newell, R. H.; McNevin, M. J.; Muckerman, J. T.; Rakowski DuBois, M.; DuBois, D. L. J. Am. Chem. Soc. 2005, 127, 358.
(18) Zhu, W.; Marr, A. C.; Wang, Q.; Neese, F.; Spencer, D. J. E.; Blake, A. J.; Cooke, P. A.; Wilson, C.; Schröder, M. Proc. Natl. Acad. Sci. U.S.A. 2005, 102, 18280.
(19) Zampella, G.; Greco, C.; Fantucci, P.; De Gioia, L. Inorg. Chem. 2006, 45, 4109.
(20) Wilson, A. D.; Shoemaker, R. K.; Miedaner, A.; Muckerman, J. T.; DuBois, D. L.; DuBois, M. R. Proc. Natl. Acad. Sci. U.S.A. 2007, 104, 6951.
(21) Siegbahn, P. E. M.; Tye, J. W.; Hall, M. B. Chem. Commun. 2007, 101, 1752.
(22) Thomas, C. M.; Daresbourg, M. Y.; Hall, M. B. J. Inorg. Biochem. 2007, 101, 4414.
(23) Xia, Y.; Chen, S.; DuBois, M. R.; Bullock, R. M. J. Am. Chem. Soc. 2010, 132, 12716.
(24) Yang, J. Y.; Chen, S.; Dougherty, W. G.; Kassel, W. S.; Bullock, R. M.; DuBois, D. L.; Raueği, S.; Rousseau, R.; DuBois, M.; Rakowski DuBois, M. Chem. Commun. 2010, 46, 8618.
(25) Bruschi, M.; Zampella, G.; Greco, C.; Bertini, L.; Fantucci, P.; De Gioia, L. In Encyclopedia of Inorganic and Bioinorganic Chemistry; John Wiley & Sons, Ltd: Chichester, U.K., 2011.
(26) Fernandez, L. E.; Horvath, S.; Hammerschaffer, S. J. Phys. Chem. C 2012, 116, 3171.
(27) Raugei, S.; Chen, S.; Ho, M.-H.; Ginovska-Pangovska, B.; Rousseau, R. J.; DuBois, M.; DuBois, D. L.; Bullock, R. M. Chem.— Eur. J. 2012, 18, 6493.
(28) Horvath, S.; Fernandez, L. E.; Soudackov, A. V.; Hammerschaffer, S. Proc. Natl. Acad. Sci. U.S.A. 2012, 109, 15663.
(29) Fernandez, L. E.; Horvath, S.; Hammerschaffer, S. J. Phys. Chem. Lett. 2013, 4, 542.
(30) Chen, S.; Ho, M.-H.; Bullock, R. M.; DuBois, D. L.; Dupuis, M.; Rousseau, R.; Raugei, S. ACS Catal. 2013, 3, 229.
(31) Horvath, S.; Fernandez, L. E.; Appel, A. M.; Hammerschaffer, S. Inorg. Chem. 2013, 52, 3643.
(32) Kochem, A.; Neese, F.; van Gastel, M. J. Phys. Chem. C 2014, 118, 2350.
(33) Barton, B. E.; Olsen, M. T.; Rauchfuss, T. B. J. Am. Chem. Soc. 2008, 130, 16834.
(34) Barton, B. E.; Rauchfuss, T. B. Inorg. Chem. 2008, 47, 2261.
(35) Olsen, M. T.; Barton, B. E.; Rauchfuss, T. B. Inorg. Chem. 2009, 48, 7507.
(36) Olsen, M. T.; Rauchfuss, T. B.; Wilson, S. R. J. Am. Chem. Soc. 2010, 132, 17733.
(37) Carroll, M. E.; Barton, B. E.; Rauchfuss, T. B.; Carroll, P. J. Am. Chem. Soc. 2012, 134, 18843.
(38) van der Vlugt, J. I.; Rauchfuss, T. B.; Whaley, C. M.; Wilson, S. R. J. Am. Chem. Soc. 2005, 127, 16012.
(39) Justice, A. K.; Zampella, G.; Gioia, L. D.; Rauchfuss, T. B. Chem. Commun. 2007, 2019.
(40) Wang, W.; Nilges, M. J.; Rauchfuss, T. B.; Stein, M. J. Am. Chem. Soc. 2013, 135, 3633.
(41) Fraze, K.; Wilson, A. D.; Appel, A. M.; Rakowski DuBois, M.; DuBois, D. L. Organometallics 2007, 26, 3918.
(42) Liu, T.; Wang, X.; Hoffmann, C.; DuBois, D. L.; Bullock, R. M. Angew. Chem. Int. Ed. 2014, 53, 5300.
(43) Barton, B. E.; Zampella, G.; Justice, A. K.; De Gioia, L.; Rauchfuss, T. B.; Wilson, S. R. Dalton Trans. 2010, 39, 3011.
(44) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, J. A., Jr.;
