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Misconception of reductive elimination of H₂, in the context of the mechanism of nitrogenase

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Abstract

The elimination of H₂ from an M(H)₂ component of a coordination complex is often described as reductive elimination, in which the H atoms are regarded as hydride ions, and the product complex after elimination is regarded as reduced by two electrons. The concept is $M^{n+2}(H^-)_2 \rightarrow M^n + H_2$ (with oxidative addition as its reverse). This interpretation contravenes Pauling's electroneutrality principle, and a number of researchers of metal-hydrogen systems have warned against literal acceptance of the formalism. A mechanism suggested by others for the chemical catalysis occurring at the Fe₇MoS₉C active site cluster of nitrogenase has invoked reductive elimination of H₂ from Fe as a central premise. I report here calculations of atom partial charges during the relevant nitrogenase steps, as well as atom partial charges for some well-studied Fe complexes that model the nitrogenase chemistry. Fe-coordinated H atoms are < 20% hydridic, and during the H₂ elimination process the charge on Fe is essentially invariant. The argument for literal reductive elimination of H₂ as part of the mechanism of nitrogenase is not sustained.

Introduction

This paper assesses the concept of reductive elimination (and its reverse, oxidative addition) as applied to complexes containing H and H₂ ligands, and as invoked as part of the chemical mechanism of the enzyme nitrogenase. The formalism of reductive elimination/oxidative addition is founded in the assignment of atomic oxidation states within a molecular assembly, and as such is questionable.

In the rich chemistry of metal complexes containing H and/or H₂ ligands there occur fundamental transformations $M + H_2 \leftrightarrow M(H)_2$, and in M(H)₂ the ligands are sometimes regarded as hydrides, H⁻, and the metal is regarded as undergoing a two electron change: that is, the reaction is conceptualised as $M^n + H_2 \leftrightarrow M^{n+2}(H^-)_2$. However, Crabtree had early misgivings about the labelling of some reactions as oxidative addition,^{1,2} and provided NMR evidence that addition of H₂ to [Ir(cod)L₂]⁺ complexes (cod = 1,5-cyclooctadiene, L = phosphine, amine, olefin) was slightly reductive rather than oxidative at Ir.¹ Crabtree proposed nomenclature that did not presume oxidative character.² In their comprehensive review of the reactions of transition metal dihydrogen complexes, Jessop and Morris endorsed the Crabtree interpretation, and stated "it is better to refer to $M + H_2 \rightarrow M(H)_2$ as a homolytic splitting in preference to an oxidative addition."³ In 1984, immediately after the report of the first transition metal H₂ complex, Yves Saillard and Roald Hoffmann⁴ interpreted the addition of H₂ to a metal with the comment "Formalisms are convenient fictions which contain a piece of the truth - and it is so sad that people spend a lot of time arguing about the deductions they draw, often ingeniously and artfully, from formalisms, without worrying about their underlying assumptions. The "complex" or dative bonding picture which led to "oxidation at metal" of course is an exaggeration. The M-H σ bonds are in good part

covalent. To the extent that they are so, the real d electron population at the metal moves back from d^{n-2} toward d^n . To the extent that it probably never quite gets back to d^n it is still informative to call this an oxidative addition. What the "oxidative addition" formalism conceals and a molecular orbital picture reveals is that in the course of this reaction there has to be a two-way flow of electron density, from the metal to the new ligands and in the reverse direction."

Remember the wisdom of Linus Pauling:^{5,6} "I have accordingly formulated the *postulate of the essential electrical neutrality of atoms* : namely, that the electronic structure of substances is such as to cause each atom to have essentially zero resultant electrical charge, the amount of leeway being not greater than about $\pm 1/2$, and these resultant charges are possessed mainly by the most electropositive and electronegative atoms, and are distributed in such a way as to correspond to electrostatic stability." "I doubt whether the ferrous ion and ferric ion, and similar ions of the transition elements, exist in chemical substances. I think instead that the atoms of iron in all ferrous and ferric compounds form covalent bonds in such a way as to remain essentially neutral."⁵ Through analysis of experimental ionisation potentials, ligand-field perturbations, and spin-orbit coupling-constant data for conventional complexes of first row transition metals, Tom Dunn concluded that the Pauling electroneutrality principle was strongly supported.⁷

The formalisms of reductive elimination and oxidative addition have been used for many ligands X other than H, and in cases where X has high electronegativity (and M low electronegativity), a degree of change in the electron population and charge of M and X has some validity. However H has the lowest electronegativity of these formally anionic ligands X (pointed out by Hlatky and Crabtree in their comprehensive review of transition metal polyhydride complexes⁸), and the difference in electronegativity between H and a metal such as Fe (relevant for nitrogenase) is relatively small, of order 0.3.

The standard molecular orbital theory for $M(H_2)$ and $M(H)_2$ bonding is outlined in Fig 1.^{4,9} For $M(H_2)$ bonding the filled σ -bonding of H_2 overlaps an empty metal d orbital with σ symmetry towards H_2 , and a filled metal d orbital with π symmetry back-donates into the empty σ^* orbital of H_2 . A key property of the $M(H_2) \leftrightarrow M(H)_2$ system is variable H--H distance, ranging from 0.8 - 1.0 Å through 1.1 - 1.6 Å ('stretched H_2 ' to 'compressed dihydride') to >1.6 Å (separated H atoms).^{3,10,11} All of these occurrences are readily interpreted in terms of varying contributions of the H--H bonding and antibonding interactions in Fig 1, consequent upon the degree of back-donation controlled by the other ligands on M and the identity of M. In the limit, $M(H)_2$ where bonding between the two H atoms is lost, the bonding picture involves simply the 1s orbital of each H overlapping with approximately orthogonal metal σ orbitals and the formation of two polar covalent M-H bonds. This theoretical model, and particularly the role of back-donation, has enabled the interpretation of diverse properties of H_2 complexes, as described by Kubas in his book¹² and major review.¹³

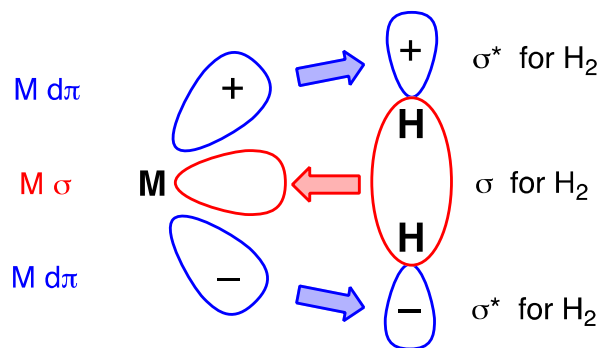


Fig. 1. The basic molecular orbital theory of $M(H_2)$ and $M(H)_2$ bonding.

Despite the early warnings, the concepts of reductive elimination/oxidative addition pervade the literature on metal-hydrogen systems, with some belief that there is two-electron change at the metal. One instance is in the mechanism of the enzyme nitrogenase. Nitrogenase¹⁴⁻²¹ catalyses the conversion of N₂ to NH₃, with concomitant formation of H₂ by reduction of protons. The active site where these reactions occur is FeMo-co, shown in Fig 2. Much experimental knowledge has been accumulated^{20,22} on the biochemical kinetics,²³⁻³⁰ on the structures of the MoFe protein and the Fe protein that comprise the enzyme, on the unusual and unprecedented structure of FeMo-co,³¹⁻³⁴ and about significant surrounding residues that are in some way involved in the reactivity.^{20,35} Investigations by Seefeldt and colleagues have established that the 'front' Fe₂,Fe₃,Fe₆,Fe₇ face of FeMo-co, underneath the side chain of α -70^{Val}, is the reaction zone, with Fe₂ and Fe₆ being the metal atoms most probably involved in catalytic activity.^{36-39,20,35,40} A number of intermediates have been trapped using altered forms of the MoFe protein, and analysed spectroscopically.^{39,41,20,42-47} Despite this substantial knowledge-base, the mechanism of hydrogenation of N₂ to NH₃ (and hydrogenation of other non-physiological substrates^{14,15,48-51}) is not yet understood at the chemical level. In vitro synthesis of the FeMo-co cluster, a pre-requisite for directly relevant model studies, is still to be achieved. Chemical mechanisms for the hydrogenation reactions have been developed, based on theoretical simulations, general knowledge of relevant coordination chemistry, and analysis of the surrounding protein structure.⁵²⁻⁵⁸

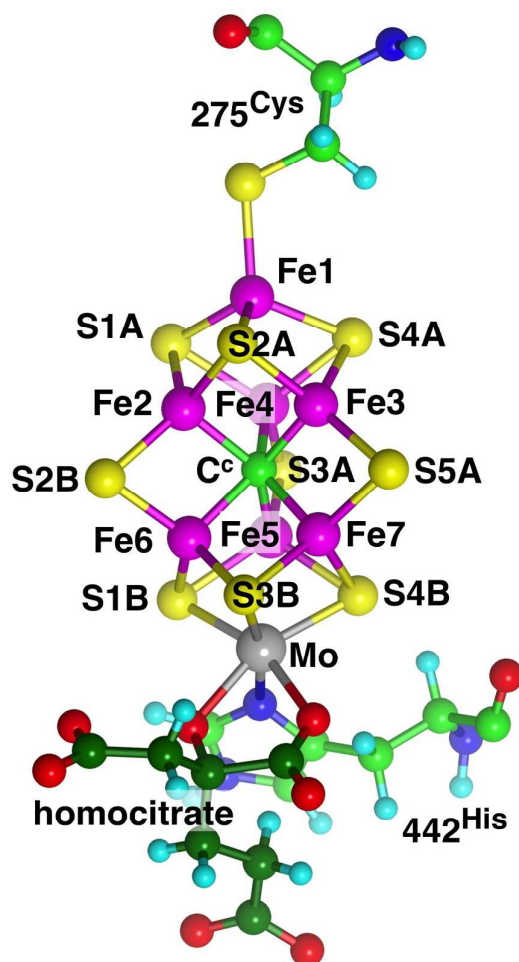
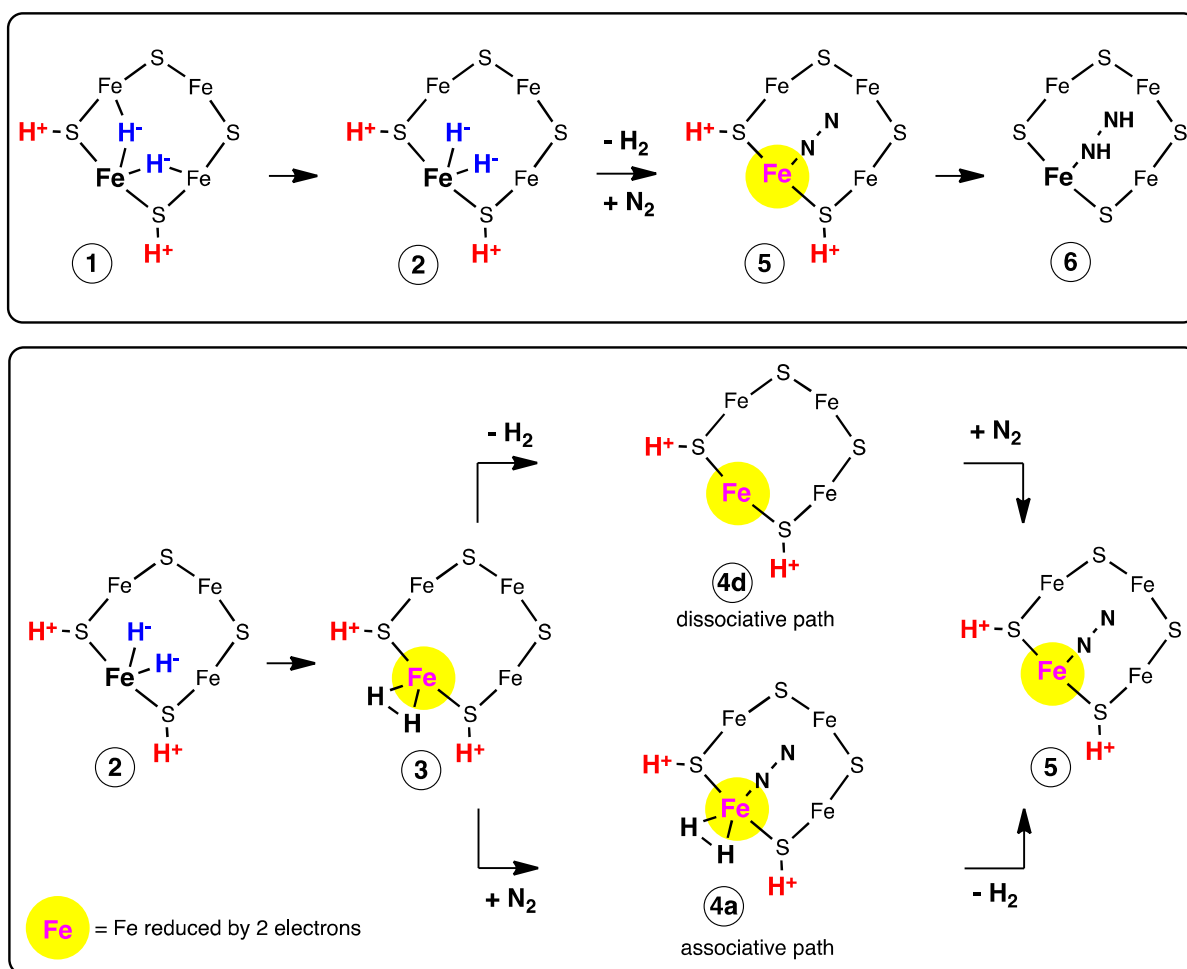


Fig. 2. The structure of FeMo-co, the active site of nitrogenase.

Hoffman *et al*⁵⁹⁻⁶¹ have proposed a mechanism premised on the steps shown in the upper panel of Scheme 1. There is evidence that the binding of N₂ to FeMo-co occurs after addition of four electrons and four protons to FeMo-co: this is the E₄H₄ state in the mechanistic scheme developed by Thorneley and Lowe from their extensive kinetic measurements of enzyme reactions.²³⁻²⁶ Hoffman *et al* regard the four H

atoms in E_4H_4 as a combination of two protons bound to bridging S atoms of FeMo-co and two hydride ions coordinated to Fe (structure **1**). Scheme 1 takes FeMo-co from its E_4H_4 state to the bound N_2H_2 state, with concomitant evolution of H_2 , and without further introduction of electrons. The lower panel of Scheme 1 shows additional intermediates, not explicitly included in the original papers, but which would be required for the passage from **2** to **5**: the replacement of H_2 by N_2 could occur by dissociative or associative mechanism. The essential attribute of this mechanism is reductive elimination of H_2 , in which two hydride ions H^- bound to Fe transfer their negative charge to Fe, reducing it by two electrons. It is argued that this activates the bound N_2 with increased negative charge, favouring its protonation by adjacent $S-H^+$, leading to the N_2H_2 intermediate **6** in which Fe has returned to its resting oxidation state.



Scheme 1. Upper panel: The sequence of species proposed by Hoffman *et al.*⁵⁹⁻⁶¹ **1** is the structure of E_4H_4 indicated by spectroscopy, with two H^- ligands (blue) bridging Fe and two protons (red) on S; in **2** the two hydrides bond to one Fe atom; process **2** \rightarrow **5** is reductive elimination of H_2 from Fe, leaving that Fe reduced by two electrons (yellow highlight); at **5**, N_2 binds to and is activated by the reduced Fe; at **6** protons transfer from S to the activated N_2 . Lower panel: intermediates in the pathway from **2** to **5**; formation of H_2 on Fe, followed by either a dissociative or associative replacement of H_2 by N_2 . Only the front Fe_4S_4 face of FeMo-co is shown, and specific stereochemistries are not implied.

A direct way to assess these theories is by calculation of the atom partial charges. Surprisingly, such calculations are rarely reported in the literature,^{62,63} and so I present here calculations that bear on the

charges of the atoms involved, both in FeMo-co complexes (Scheme 1) and in experimental model systems.

Methods

All density functional calculations use the DMol methodology of Delley,⁶⁴⁻⁶⁸ with accurate double numerical (dnp) basis sets.⁶⁷ The calculations are all electron, spin-unrestricted, with no imposed symmetry, and use the blyp^{69,70} functional. The real-space cutoff for calculation of atomic basis sets was 4.76Å, and a fine integration mesh was used. For the monometallic model complexes reported here the experimental spin state was specified. Bianchini *et al*⁶² used analogous DMol methods to examine the bonding and charge distribution in Fe- and Ru-(H)(H₂) complexes with a tripodal tetraphosphine ligand.

The calculational model of FeMo-co is the same as that used previously, retaining the essential coordination of all atoms: cysteine-275 is truncated to -SMe, histidine-442 is truncated to imidazole, and homocitrate is truncated to -OCH₂COO⁻. The net charge on this model is -4 (*ie* core [Fe₇MoS₉C]⁻), which corresponds to the resting state of FeMo-co.^{71,72} The electronic states of the ligated FeMo-co structures are controlled through input specifications of the signs and magnitudes of the Fe spin densities to be used at the start of the SCF convergence calculation: these spin densities are refined in the subsequent optimisation. The net spin S is controlled through occupations of the unrestricted α and β orbitals in the usual way. Details and validation information have been published.^{73,52,74-76}

Atom partial charges were calculated using Mulliken population analysis⁷⁷ and the Hirshfeld partitioning scheme.⁷⁸ Atomic point charges calculated by fitting them to the molecular electrostatic potential (ESP) are found to be sensitive to the choices of internal and external atom radii, and, being less reliable, are not reported here. Critical assessments of concepts and methods for evaluating atomic charges in molecules are available.^{79,80} The COSMO continuum solvation model⁸¹⁻⁸³ was tested: the calculated charges are effectively independent of the dielectric constant in the range up to ϵ 80. Inclusion of COSMO solvation is important for the geometry of weak bonds involving FeMo-co.

Model complexes: calculated charges

Since the early 1970s, a remarkably rich literature has accumulated detailed descriptions and understanding of complexes of Fe (and Ru, Os) containing phosphine ligands and various combinations of H, H₂ and N₂ ligands: these complexes serve as models for the transformations of Scheme 1. Some key references are^{84,8,85-87,3,88-93,13,94,11,95,96}.

Fig. 3 presents a sequence of four complexes, containing first four H atoms, then two H plus H₂, then two H after dissociation of H₂, and finally with η^1 coordination of N₂ at the empty coordination position. The first, **PR-1**, is hypothetical because it has not been prepared with Fe, but is well characterised for Os, including neutron diffraction determination of H atom positions.⁹⁷ Calculated charges for structure **PR-1** containing Os and Fe are very similar, and therefore the results for the sequence of four structures containing Fe is presented. The conversions **PR-2** \leftrightarrow **PR-3** + H₂ and **PR-2** + N₂ \rightarrow **PR-4** + H₂ have been described.⁸⁴ Complex **PR-2** has been studied in detail by a variety of techniques revealing the rotational dynamics of η^2 -H₂, a 'cis interaction' between H₂ and H₃, and hydrogen fluxionality.^{98,99} The X-ray diffraction structure of **PR-4** is known.⁹⁹

In the figures that follow, Mulliken and Hirshfeld charges are both displayed. The calculated charges in Fig. 3 indicate that the 'hydridic character' of individual H atoms averages 10-15%, and that the coordinated H₂ is effectively uncharged. Coordinated N₂ in **PR-4** has a small negative charge (ca -0.03)

at the proximal N atom and -0.15 at the distal N atom. Calculated charges at the Fe atom are all small negative: the compensating positive charge resides on the phosphine ligands, ca +0.2 per ligand (marked for **PR-1** and **PR-4** on Fig. 3), and is unchanged through the sequence.

The significant result is that the charge on Fe does not become more negative through the sequence. There is no support for the notion of metal reduction as H₂ is formed from 2H and then H₂ dissociates.

A second group of well-studied complexes with various diphosphine ligands is represented by those shown in Fig. 4.^{100,87,101,11} It is established⁹³ that the substitution of H₂ by uncharged nucleophiles occurs with a dissociative mechanism (when R = Me or Et, but not Ph¹⁰²), passing through **PR-6** as intermediate. The calculated charges for **PR-5**, **PR-6** and **PR-7** show the hydride character of individual H atoms to be 12%, coordinated H₂ to be essentially uncharged, and coordinated N₂ to have small negative charge (<-0.1) very slightly polarised negative at the distal N atom. Again, Fe with small negative charges undergoes no substantial change in charge through the sequence.

Related complexes with tripodal phosphine ligands have also been studied extensively,^{86,103,104} and a typical set⁶² is presented in Fig. 5. To my knowledge these are the only complexes of any type containing Fe-H, Fe-H₂ and Fe-N₂ ligation for which calculated charges have been reported previously. However the calculations of Bianchini *et al*⁶² simplified the ligand substituents to H, and this distorts the calculated charges, mainly at Fe (Fig. 5 (b)). Mulliken and Hirshfeld charges for the complete complexes, Fig. 5 (a), reveal the same patterns as above, namely 10% hydridic character, very small charges on bound H₂, very small negative charge on coordinated N₂, and minor change at Fe (in a positive direction!) when H₂ is substituted by N₂.

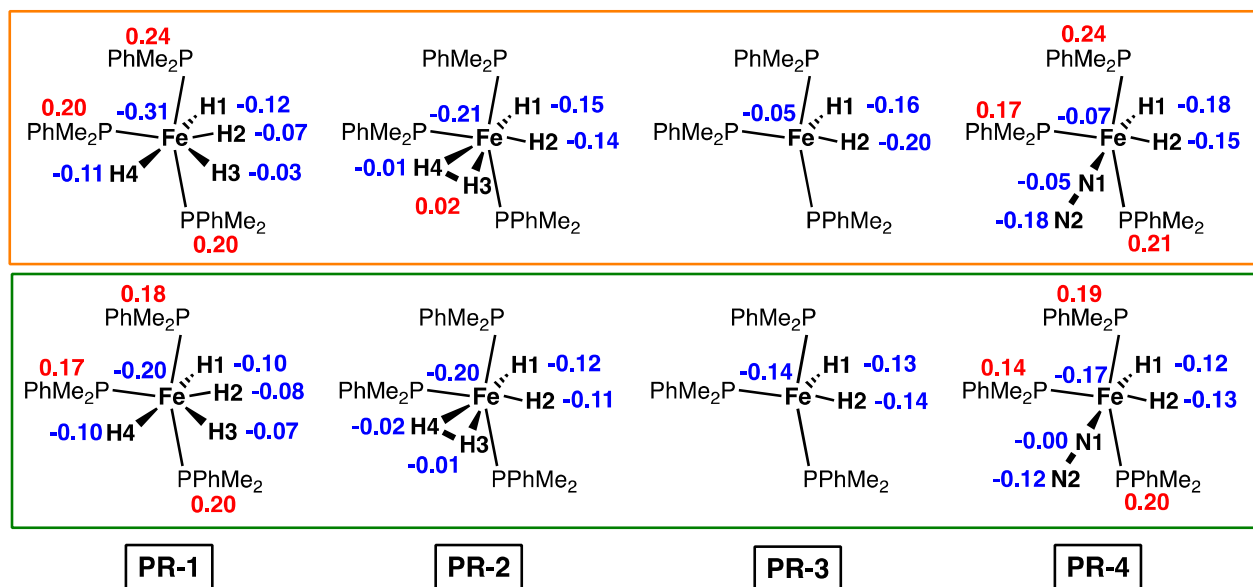


Fig. 3. Calculated charges (Mulliken, orange box; Hirshfeld green box; red positive; blue negative) for the sequence of complexes shown, involving formation of H₂ from two H atoms, dissociation of H₂, and coordination of N₂. Net charges on the PhMe₂P ligands are marked for **PR-1** and **PR-4**.

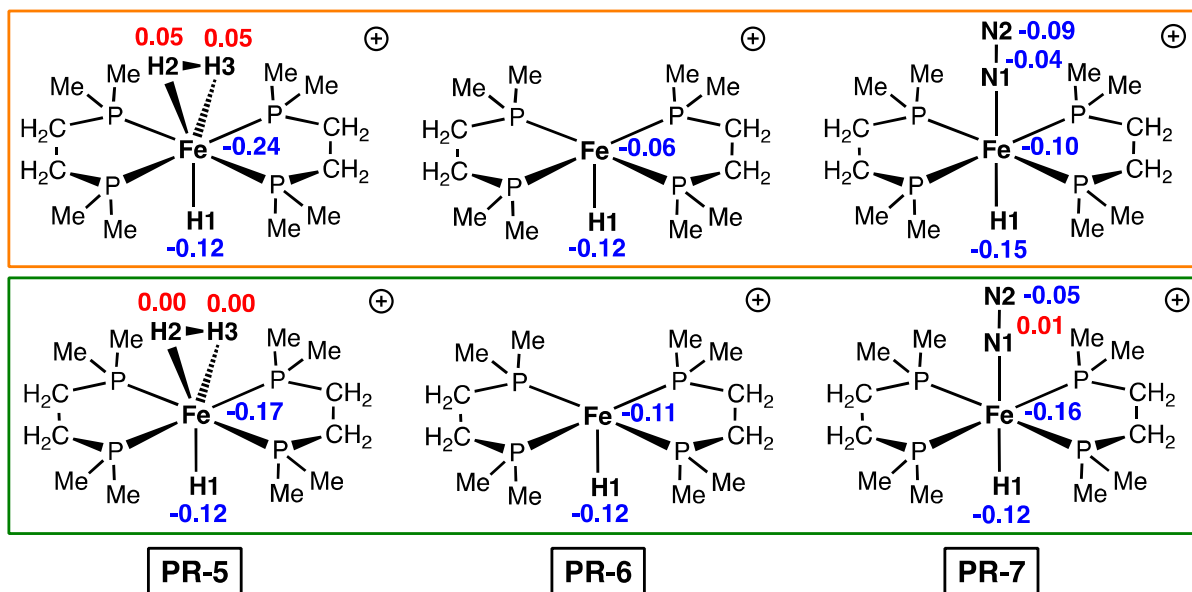


Fig. 4. Calculated charges (Mulliken, orange box; Hirshfeld green box; red positive; blue negative) for the complexes shown.

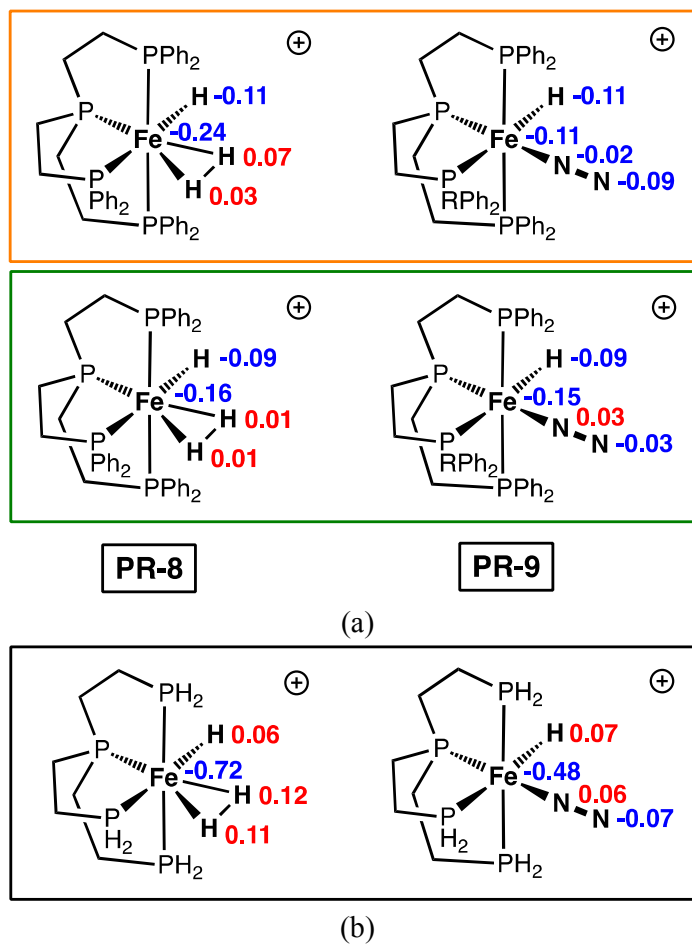


Fig. 5. (a) Mulliken and Hirshfeld charges for the typical complexes shown. (b) The Mulliken charges calculated by Bianchini *et al.*⁶² with ligand phosphine substituents as H.

FeMo-co complexes: calculated charges

In the hydrogenation reactions catalysed by FeMo-co the atoms that carry hydrogen atoms are most probably Fe6, Fe2, S2B and S3B. A mechanism has been described for the supply of protons from the protein surface to the active face of FeMo-co, via S3B, where, concomitant with electronation of FeMo-co, a hydrogen atom is generated and is subsequently able to migrate to Fe6, S2B and Fe2.^{63,105,55} In this way the E_nH_n ($n = 1 - 4$) states of FeMo-co can be generated.⁵⁸ The charge states of these hydrogen atoms on FeMo-co are calculated in the results to follow.

The S3B atom of FeMo-co triply-bridges Fe6, Fe7 and Mo. Previous calculations have shown that on protonation of S3B, one of the S3B-Fe bonds is elongated, such that doubly-bridging SH is the stable form.⁷⁵ This conversion of μ_3 -S to μ -SH on protonation is a general phenomenon.^{106-108,76,109} There are four main stable configurations for S3B-H, shown in Fig. 6, and they are represented in the charge results presented.

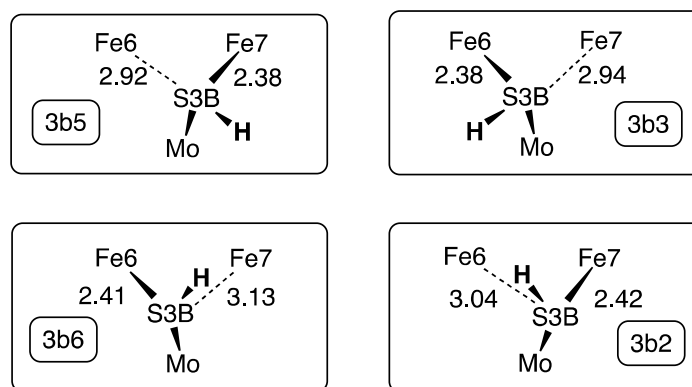


Fig. 6. The four stable configurations for doubly-bridging S3B-H, with typical distances (Å) to Fe6, Fe7.⁷⁵ Configurations are labelled as a clockface, counterclockwise. 3b3 and 3b5 are *exo*, 3b2 and 3b6 are *endo*, relative to the long S--Fe interaction.

The derivatives of FeMo-co to be described were controlled to be in a low energy electronic state (Fe1 - Fe7 spin density signs are +, -, +, -, +, -, -), and the observed¹¹⁰ net spin state $S=1/2$. Since Fe6 is ligated in almost all structures its spin density is lower than that of other Fe atoms, and in some cases optimises as small positive rather than small negative. Results presented in ESI Fig. S1 show that calculated charges are effectively independent of the electronic and spin state of the complex.

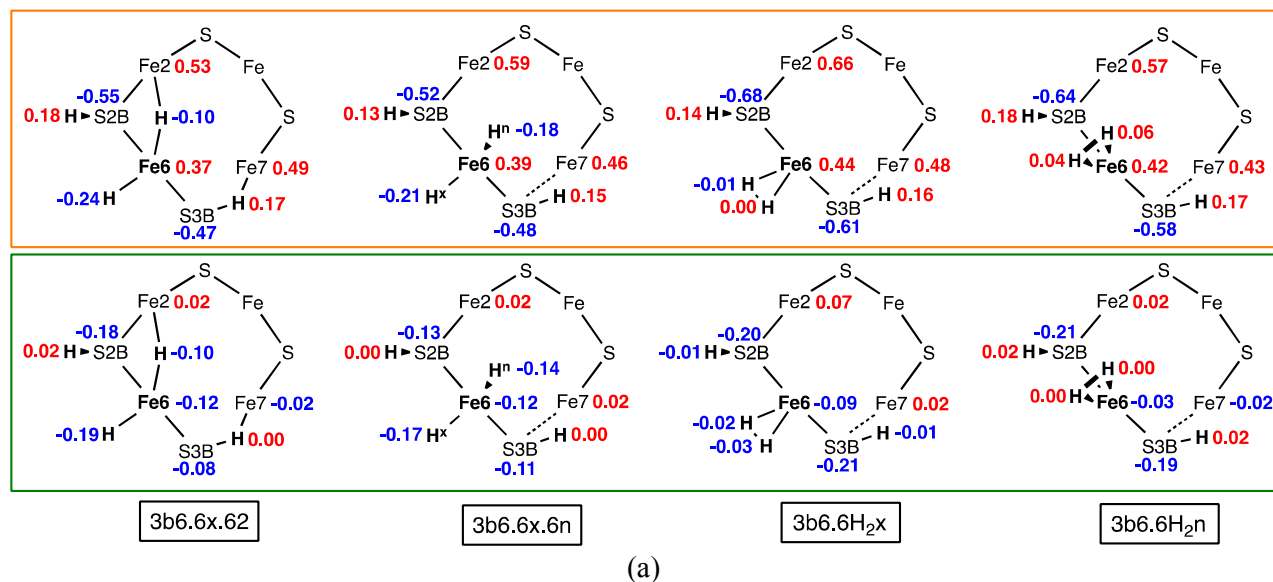
In the pictorial representations of calculated charges, only the atoms of the Fe_4S_4 cycle are shown. The notation for structure labelling is [3bz.α.β.γ] where z is the S3B-H configuration (Fig. 6), and α, β, γ.. are the locations of H atoms, bound H_2 and bound N_2 , with x/n signifying *exo/endo* and 1/2 signifying η^1/η^2 coordination: S2B-H occurs in all structures and is not explicit in the labels. Charges calculated by the Mulliken (M) and Hirshfeld (Hf) methods are presented: the values for hydrogen and nitrogen atoms are similar, and the largest differences occur at the iron and sulfur atoms, with the M method calculating larger polarisation of Fe-S bonds.

A variety of structures has been evaluated, with H atoms on S2B, S3B, Fe6, Fe2, H_2 bound in *exo* and *endo* positions, and N_2 bound in η^1 and η^2 modes and in *endo* and *exo* positions. The most relevant results are contained in Figs 7, 8 and 9: additional results are in ESI Figures S2 and S3. Fig. 7 (a) shows charges for two $(FeH)_2(SH)_2$ isomers (**2** in Scheme 1) and two $(FeH_2)(SH)_2$ isomers (**3** in Scheme 1), for the 3b6 configuration of S3B-H. Corresponding results for the 3b2 and 3b3 configurations are shown in Figs 8 and 9 (a). H atoms on S2B and S3B have Mulliken charges ranging +0.11 to +0.19 (M), while the Hirshfeld calculation yields charges in the range -0.02 to +0.02. At Fe, both methods calculate H atoms to be charged in the range -0.10 to -0.24, and H_2 molecules to be -0.06 to + 0.07. Thus the mean

'protonic' character of H on S is < 10%, and the mean 'hydridic' character of H atoms on Fe is ca 15%, and the coordinated H_2 molecules are effectively uncharged.

Figures 7 (b), 8 and 9 (b) then show the calculated charges after dissociation of H_2 (**4d** in Scheme 1), and subsequent coordination of N_2 (**5** in Scheme 1). The charges of H atoms on S2B and S3B are unchanged by these processes. At Fe6, where the dissociation and association occur, the charge becomes slightly more *positive* on dissociation of H_2 : the largest change is +0.17 (M) in the step **3b3.6H₂n** \rightarrow **3b3**, but in general the Mulliken charge increases by ca 0.1 unit and the Hirshfeld charge becomes more positive by < 0.05 unit on dissociation of H_2 . After association of N_2 the charge at Fe6 is effectively unchanged, albeit with some small variations depending on the type of N_2 coordination. When N_2 is bound η^2 , in either the *endo* or *exo* positions, the charges on the N atoms are calculated (by both methods) to be in the range -0.11 to -0.21, while η^1 - N_2 is calculated to be ca -0.02 at the proximal N atom and ca -0.2 at the distal N atom.

Figure 9 (c) shows calculated charges for structures with both H_2 and N_2 bound at Fe6. These are analogous to **4a** in Scheme 1. There are no significant differences in the calculated charges at Fe, H_2 and N_2 relative to the corresponding structures with only H_2 (**3**) or N_2 (**5**), or neither (**4d**).



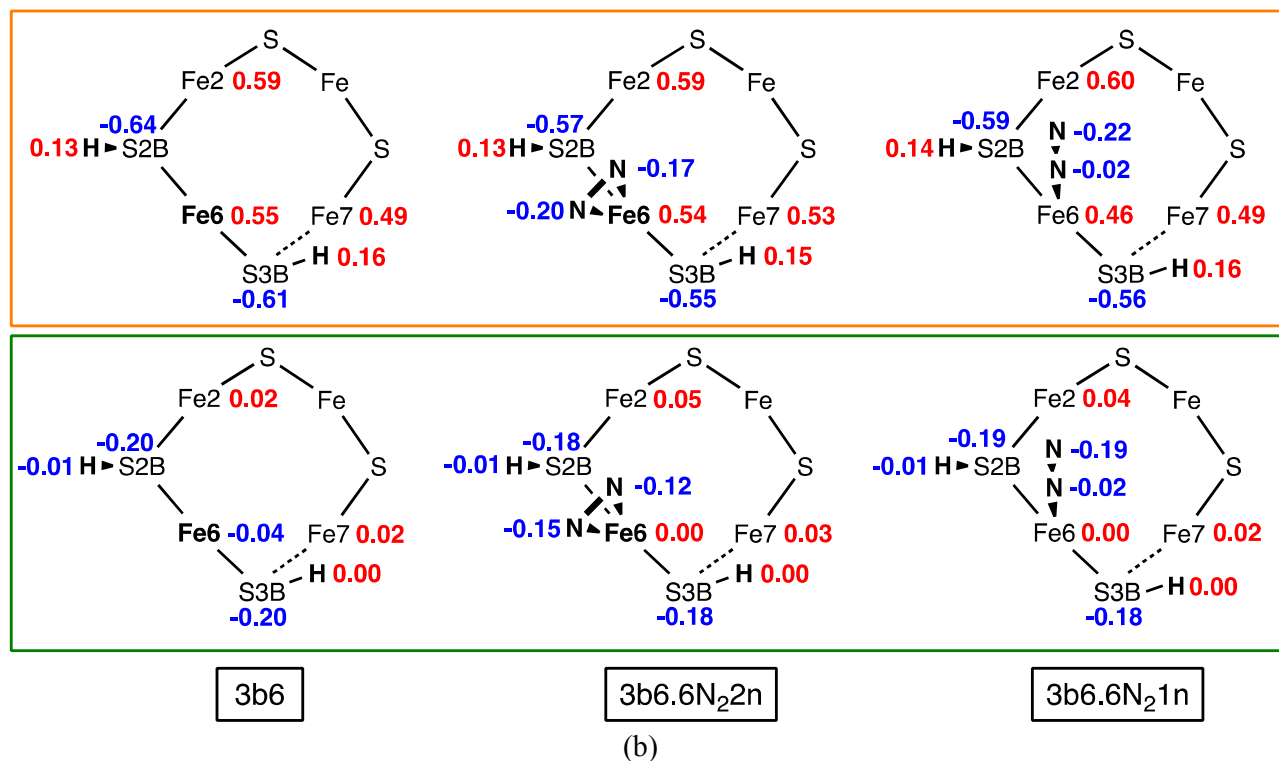


Fig. 7. (a) Calculated charges (Mulliken, orange; Hirshfeld green) for four structures with either H atoms or H₂ on Fe, and S3B-H in configuration 3b6: H^x is *exo*-H, Hⁿ is *endo*-H. (b) Calculated charges after dissociation of H₂, and addition of N₂.

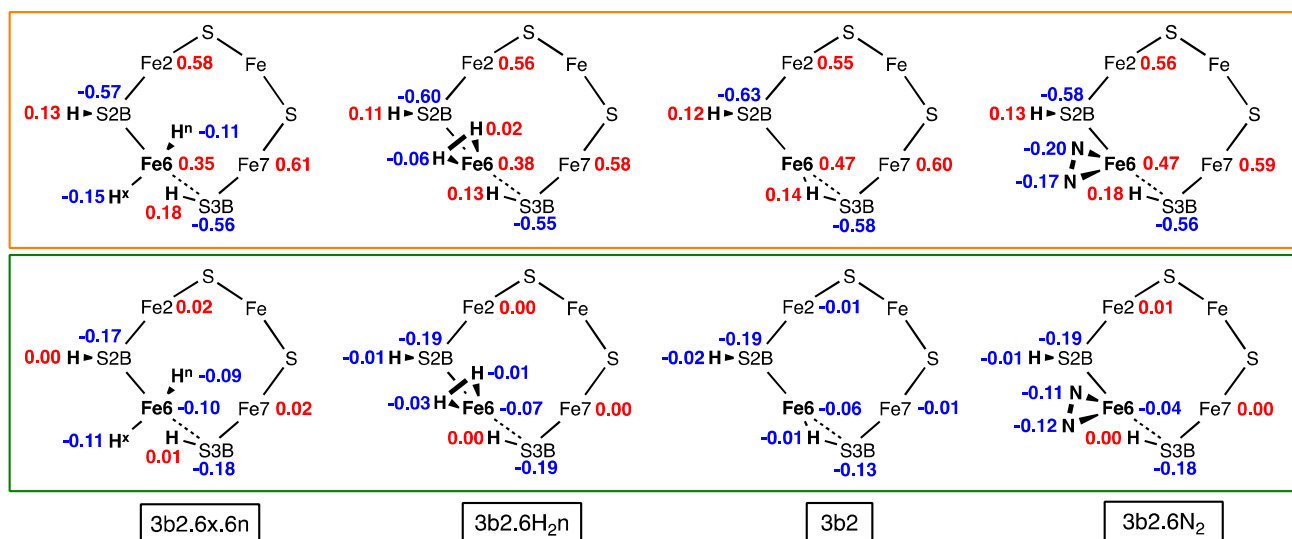
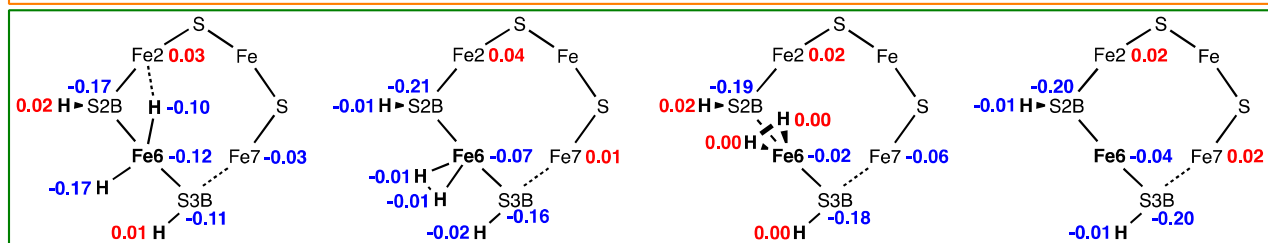
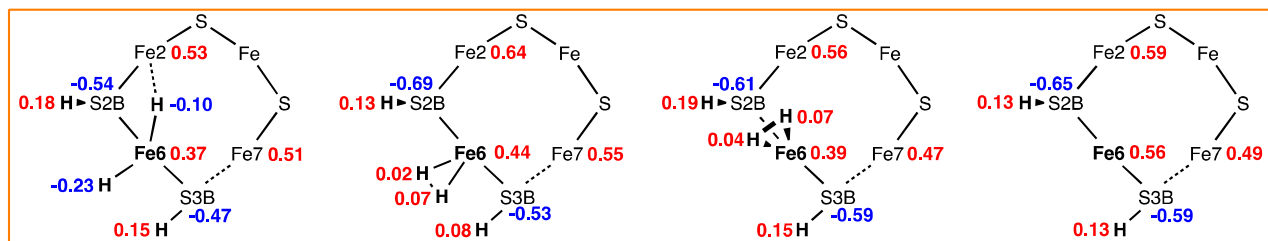


Fig. 8. Calculated charges (Mulliken, orange; Hirshfeld green) for structures in which H₂ is formed from Fe(H)₂, H₂ dissociates, and N₂ coordinates, with S3B-H in configuration 3b2.

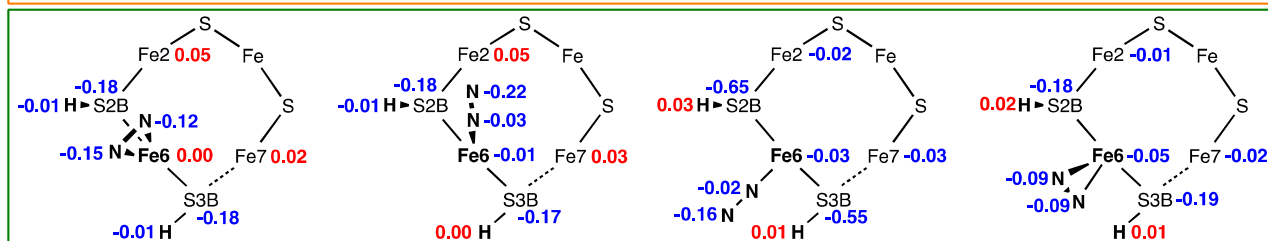
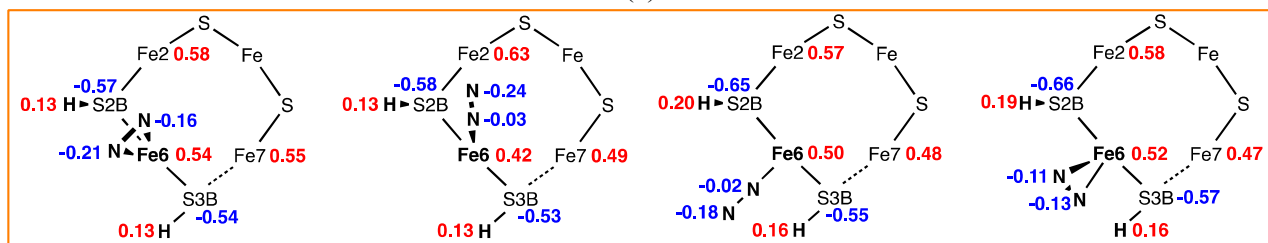


3b3.6x.62

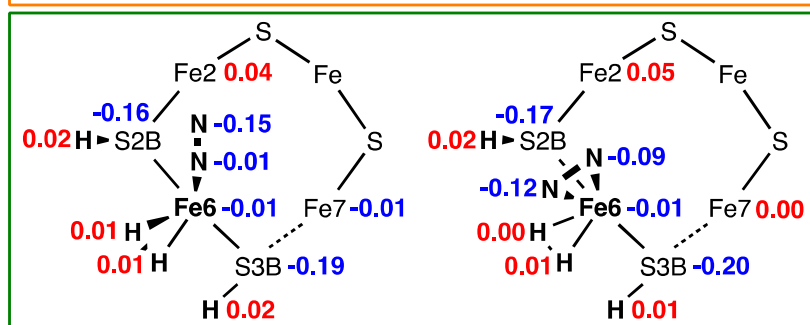
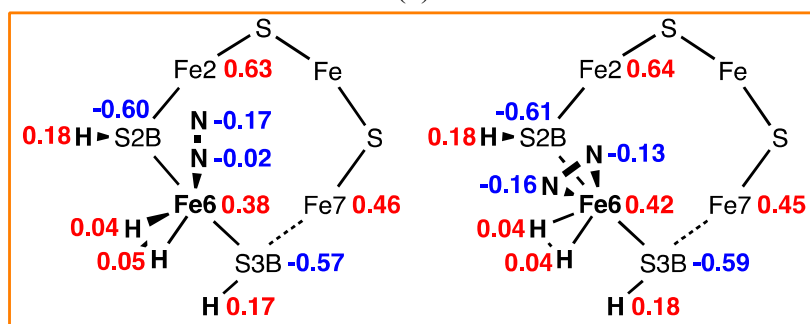
3b3.6H₂x3b3.6H₂n

3b3

(a)

3b3.6N₂2n3b3.6N₂1n3b3.6N₂1x3b3.6N₂2x

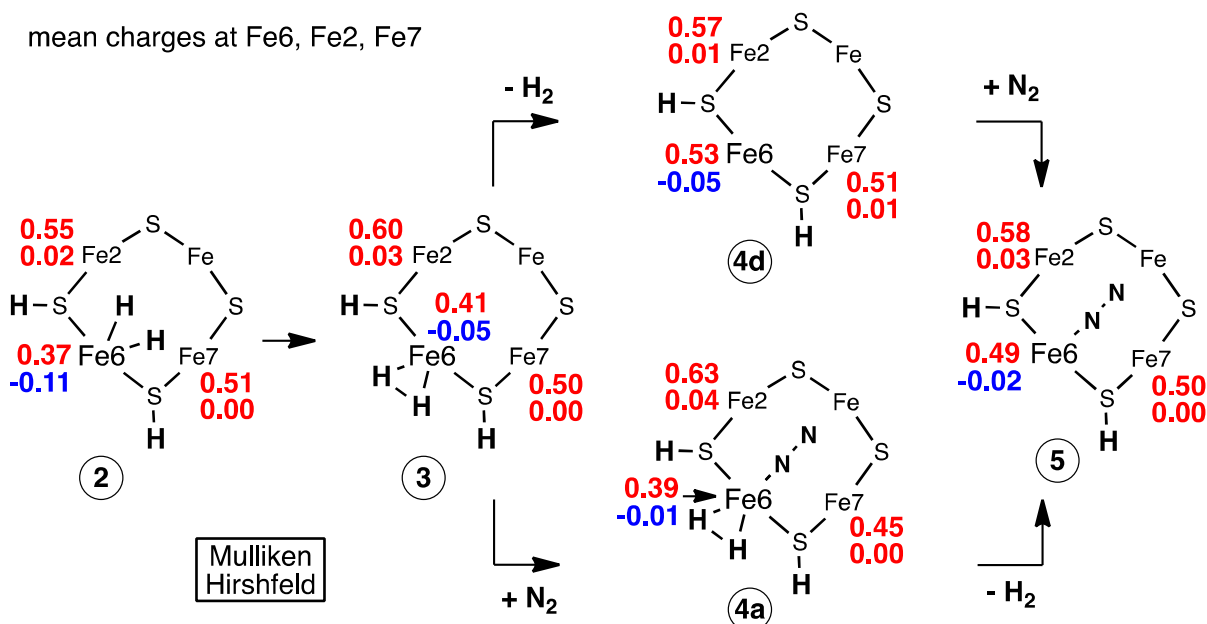
(b)

3b3.6H₂x.6N₂1n3b3.6H₂x.6N₂2n

(c)

Fig. 9. Calculated charges (Mulliken, orange; Hirshfeld green) for structures with S3B-H in configuration 3b3. (a) Structures with Fe(H)₂, FeH₂, and dissociated H₂. (b) Structures with N₂ bound after dissociation of H₂. (c) Structures with bound H₂ and bound N₂.

The key to evaluation of the reductive elimination concept here is the change in charge state of the iron atom that undergoes the sequence of reactions of Scheme 1. Scheme 2 collects the mean values of the Mulliken and Hirshfeld charges at the reactive iron atom Fe6, and, for comparison, the values at adjacent Fe2 and Fe7. Clearly there is but minor change in the Fe charge states, and the small change occurs in the direction opposite to that expected for reductive elimination.



Scheme 2. Mean values for the calculated charges on Fe6, Fe2 and Fe7 in the sequence of transformations 2 → 3 → 4d/4a → 5. Mulliken charges are labelled above Hirshfeld charges.

Discussion

The notion of reductive elimination of hydrogen, as $M^{n+2}(H^-)_2 \rightarrow M^n + H_2$, occurs throughout the extensive literature on complexes containing H atoms and H₂ molecules, despite early statements from sages Pauling, Hoffmann and Crabtree. The misconceptions arise when formal oxidation states of atoms in molecules are accepted as charge states, leading to assumed distributions of charge in molecules.

Charge distributions in complexes containing H atoms and H₂ molecules are rarely reported,⁶² and therefore I have reported here the calculated atomic partial charges in some model compounds and in possible intermediates in the hydrogenation of N₂ by the enzyme nitrogenase. The conclusions are that, in these systems, the negative charge on single coordinated H atoms is not larger than -0.2, coordinated H₂ is effectively uncharged, and that in the transformation $M(H)_2 \rightarrow M + H_2$ the partial charge on M does not become more negative. These results agree with the prior expectations.^{5,6,4,1,2}

Following the discovery of metal complexes of H₂ in 1984 there has been accumulated a very large volume of experimental information on complexes containing M-H₂ and M-H entities, and in particular on the $M(H)_2 \leftrightarrow M-H_2$ relationship.^{12,13} NMR^{89,11} has shown that these interconversions, and various

coordination fluxionalities, occur on flat energy surfaces, consistent with the low charges and low bond polarities of the participants. There are electrochemical data,^{86,111} relating to changes in *molecular* charge. There are pK_a data,¹¹² on steps in which protons are transferred. DuBois *et al* constructed thermodynamic cycles from pK_a data and redox potentials to define a hydricity of M-H complexes, meaning the free-energy change associated with dissociation of H⁻ in solution,¹¹³⁻¹¹⁶ and this practice continues.¹¹⁷ However, this is a thermodynamic construct (incorporating also the free energy change for H₂ → H⁺ + H⁻) and is not indicative of the charge state of the coordinated H atom. Analogous free-energy changes are defined and evaluated for dissociation of H⁰ and of H⁺ from M-H.^{113,115,118,119}

In the context of the nitrogenase mechanism, the argument⁵⁹⁻⁶¹ that is based on reductive elimination of H₂ – " .. the departing H₂ carries away only two of the four reducing equivalents stored in E₄, while the Fe that binds N₂ becomes highly activated through formal reduction by two equivalents, for example, from formal redox states of Fe(II) to Fe(0). Such a highly reduced Fe is poised to deliver the two activating electrons to N₂ .." – is not sustained by the calculated charges. Alternative approaches based on (1) the occurrence of hydrogen atoms on FeMo-co, (2) a variety of hydrogen atom transfer steps, and (3) the formation and elimination of H₂, are able to account – qualitatively, and in many cases through density functional simulation of elementary reaction steps – for the reaction data.⁵⁷

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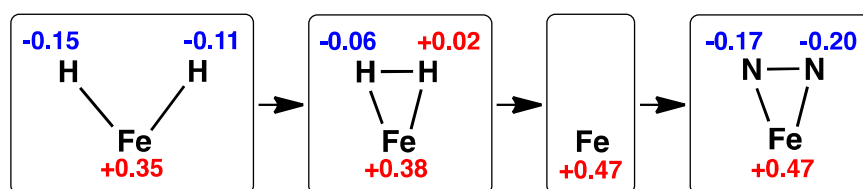
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Graphical abstract and text



Mulliken charges

Calculated atom partial charges reveal misconceptions of reductive elimination of H₂.