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# Metal vs. ligand protonation and the alleged proton-shuttling role of the azadithiolate ligand in catalytic H<sub>2</sub> formation with FeFe hydrogenase model complexes†

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Electron and proton transfer reactions of diiron complexes [Fe<sub>2</sub>adt(CO)<sub>6</sub>] (1) and [Fe<sub>2</sub>adt(CO)<sub>4</sub>(PMe<sub>3</sub>)<sub>2</sub>] (4), with the biomimetic azadithiolate (adt) bridging ligand, have been investigated by real-time IR- and UV-vis-spectroscopic observation to elucidate the role of the adt-N as a potential proton shuttle in catalytic H<sub>2</sub> formation. Protonation of the one-electron reduced complex, 1<sup>•−</sup>, occurs on the adt-N yielding 1H and the same species is obtained by one-electron reduction of 1H<sup>+</sup>. The preference for ligand vs. metal protonation in the Fe<sub>2</sub>(I,0) state is presumably kinetic but no evidence for tautomerization of 1H to the hydride 1Hy was observed. This shows that the adt ligand does not work as a proton relay in the formation of hydride intermediates in the reduced catalyst. A hydride intermediate 1HHy<sup>+</sup> is formed only by protonation of 1H with stronger acid. Adt protonation results in reduction of the catalyst at much less negative potential, but subsequent protonation of the metal centers is not slowed down, as would be expected according to the decrease in basicity. Thus, the adtH<sup>+</sup> complex retains a high turnover frequency at the lowered overpotential. Instead of proton shuttling, we propose that this gain in catalytic performance compared to the propyldithiolate analogue might be rationalized in terms of lower reorganization energy for hydride formation with bulk acid upon adt protonation.

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## Introduction

Proton binding sites in the second coordination sphere of catalytic metal centres are widely considered as an important design principle for facilitating proton coupled electron transfer in molecular catalysts for *e.g.* water splitting,<sup>1–5</sup> H<sub>2</sub> formation and activation<sup>6–12</sup> or CO<sub>2</sub> reduction.<sup>13–21</sup> For the directed design of synthetic catalysts it is, however, important to note that improvements to catalytic performance (TOF, overpotential) brought about by basic sites in the second coordination sphere are not necessarily arising from a proton relay activity. Instead, the modulation of redox and acid/base properties of the metal centre upon changes in protonation state in the second coordination sphere may be the actual origin of improved catalytic performance.<sup>14–17</sup>

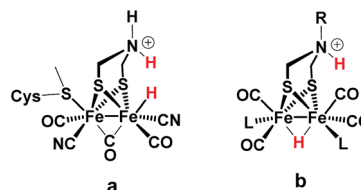
Regarding catalysts for H<sub>2</sub> formation, the N<sub>2</sub>P<sub>2</sub> ligands introduced by DuBois and co-workers,<sup>6,7,12</sup> and the azadithiolate (adt) bridging ligand in diiron complexes of the general formula Fe<sub>2</sub>adt(CO)<sub>4</sub>X<sub>2</sub> (X = *e.g.* CO, R<sub>3</sub>P) modelled after the FeFe-Hase active site,<sup>9,22–24</sup> are prominent examples of ligand motifs with basic sites in the second coordination sphere. The amine function of the adt ligand is believed to assist enzymatic H<sub>2</sub> formation and activation by shuttling of protons to or from the distal iron centre of the active site where the crucial terminal hydride intermediate is formed (Scheme 1a).<sup>25,26</sup> A similar role of the adt ligand in catalysis by the synthetic models considered here seems less likely given the preferred bridging coordination of the hydride (Scheme 1b).<sup>23</sup> The superior catalytic performance of Fe<sub>2</sub>(adt)(CO)<sub>6</sub>, 1, over its propyldithiolate (pdt)

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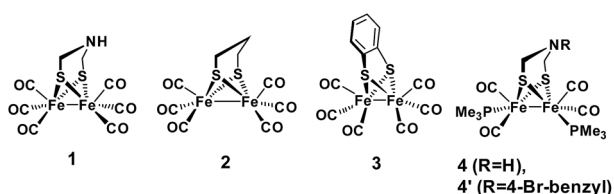
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Scheme 1 FeFe Hase active site (a) and synthetic model (b) bearing a hydride and a proton.

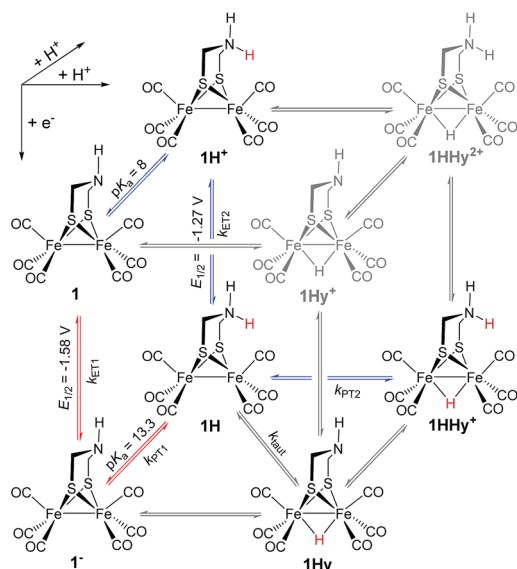


analogue **2** in electrochemical H<sub>2</sub> formation has however been attributed to proton shuttling, involving specifically terminal protonation of the metal centre by tautomerization of a *adt*-NH<sup>+</sup> precursor upon one-electron reduction of the catalyst.<sup>27</sup> We were therefore intrigued whether the proposed role of the *adt* ligand as proton shuttle and the formation of terminal hydride intermediates in these model complexes could be inferred from direct spectroscopic observation. For this purpose we have combined laser flash induced reduction as well as rapid chemical reduction of the catalyst with both UV-vis and IR detection to elucidate structure and reactivity of reduced and reduced-protonated intermediates derived from **1** (ref. 28) and Fe<sub>2</sub>(adt)(CO)<sub>4</sub>(PMe<sub>3</sub>)<sub>2</sub> (**4**).<sup>29</sup> This approach enabled us to exclude any proton shuttling role of the *adt* bridging ligand in catalytic H<sub>2</sub> formation while the kinetics of ligand and metal protonation steps suggest an alternative rationale for the improved performance.



## Results and discussion

Generally, complex **1** catalyses H<sub>2</sub> formation *via* an initial ET-PT sequence with weaker acids, or a PT-ET sequence when stronger acids are employed that initially protonate the *adt*-N with a pK<sub>a</sub> of 8 in acetonitrile (Scheme 2, potentials from ref. 27).



which avoids protonation of the neutral parent complex, shifts all three  $\nu_{\text{C-O}}$  bands by about  $20\text{ cm}^{-1}$  to higher wavenumbers ( $2025$ ,  $1965$  and  $1935\text{ cm}^{-1}$ ), as shown in Fig. 2. The magnitude of the shift is similar to what is observed upon protonation of the neutral parent complex with stronger acids (*cf.* Fig. 3a) and characteristic for protonation of the adt-N.<sup>29</sup>



Metal protonation of  $\mathbf{1}^-$  is on the other hand expected to shift the carbonyl bands by about  $80\text{ cm}^{-1}$  to higher wavenumbers. Shifts of this magnitude have been established for the bridging hydrides formed by protonation of  $\text{Fe}_2(\text{I},\text{I})$  complexes with electron donor ligands like  $\mathbf{4}'$  (ref. 35) as well as transiently generated  $\text{Fe}_2(\text{I},0)$  hexacarbonyl complexes  $\mathbf{2}^-$  and  $\mathbf{3}^-$ .<sup>32,33</sup> Mutually cancelling shifts of the carbonyl bands upon one-electron reduction and metal protonation were further evidenced with help of complex  $\mathbf{4}$  (*vide infra*). The transient IR spectrum of the protonation product hence proves that the adt ligand remains the preferred site of protonation, at least kinetically, also upon one-electron reduction of  $\mathbf{1}$ . This conclusion is corroborated by the UV-vis spectrum of  $\mathbf{1H}$  ( $\text{ESI}^\dagger$ ), which is similar to its precursor  $\mathbf{1}^-$ , while metal protonation of  $\mathbf{2}^-$  was previously shown to cause complete bleach of its visible absorption bands that arise from transitions involving predominantly metal-based orbitals. The observed pseudo-first order rate constants for formation of  $\mathbf{1H}$  follow a linear dependence on acid concentration before becoming limited by

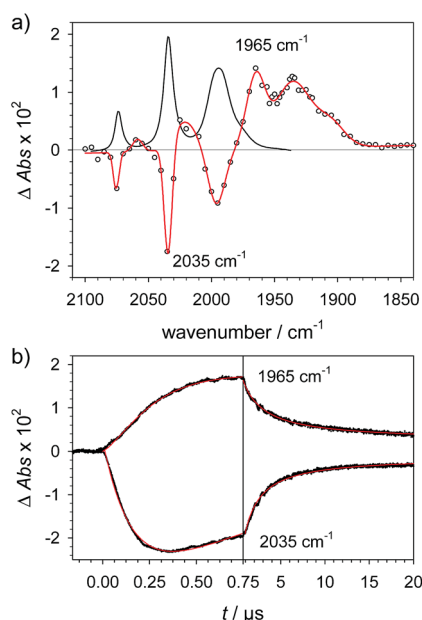


Fig. 2 (a) Transient IR spectrum  $1\text{ }\mu\text{s}$  after excitation ( $\text{O}$ ,  $\text{red}$ ) and normalized IR spectrum of the starting state ( $\text{black}$ ) for formation of  $\mathbf{1H}$  by protonation of  $\mathbf{1}^-$  with  $\text{Cl}_3\text{CCOOH}$  ( $13\text{ mM}$ ) following reduction of  $\mathbf{1}$  ( $1.3\text{ mM}$ ) by flash-quench generated  $[\text{Ru}(\text{dmb})_3]^+$  in acetonitrile. (b) Kinetic traces ( $\dots$ ) and fits ( $\text{red}$ ) monitoring pseudo-first order formation of  $\mathbf{1H}$  ( $1965\text{ cm}^{-1}$ ) and bleach of  $\mathbf{1}$  ( $2035\text{ cm}^{-1}$ ) followed by second order charge recombination with  $\text{TTF}^+$ .

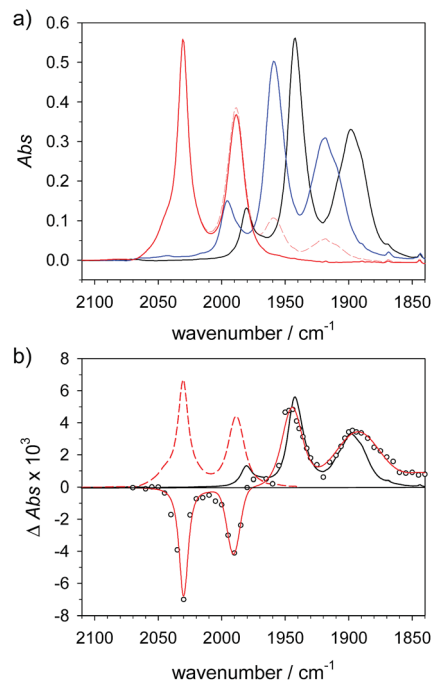


Fig. 3 (a) FTIR spectra of  $\mathbf{4}$  ( $1.5\text{ mM}$ ) ( $\text{black}$ ) in acetonitrile,  $\mathbf{4H}^+$  ( $\text{blue}$ ) obtained by protonation with toluenesulfonic acid ( $3\text{ mM}$ ), and  $\mathbf{4Hy}^+$  ( $\text{red}$ ) obtained by protonation with toluenesulfonic acid ( $3\text{ mM}$ ) in presence of tetrabutyl-ammonium chloride ( $1.5\text{ mM}$ ) after correction of the raw spectrum ( $\text{dashed red}$ ) for minor contribution from  $\mathbf{4H}^+$ . (b) Transient IR spectrum upon reduction of  $\mathbf{4Hy}^+$  to  $\mathbf{4Hy}$  by electron transfer from flash-quench generated  $[\text{Ru}(\text{dmb})_3]^+$  ( $\text{O}$ ,  $\text{red}$ ,  $1\text{ }\mu\text{s}$  after excitation) and normalized IR spectra of  $\mathbf{4Hy}^+$  ( $\text{dashed red}$ ) and  $\mathbf{4}$  ( $\text{black}$ ).

the preceding electron transfer step ( $\text{ESI}^\dagger$ ). The straightforward concentration dependence excludes any complications of the protonation kinetics due to dimerization of the acetic acids that was previously found to result in quadratic concentration dependence corresponding to an increase in effective acid strength.<sup>36</sup> Interestingly, protonation of  $\mathbf{1}^-$ , which occurs unambiguously at the adt-N, proceeds remarkably slowly with bimolecular rate constants  $k_{\text{PT1}}$  of  $4 \times 10^8\text{ M}^{-1}\text{ s}^{-1}$  and  $2 \times 10^7\text{ M}^{-1}\text{ s}^{-1}$  for  $\text{Cl}_3\text{CCOOH}$  and  $\text{ClH}_2\text{CCOOH}$ , respectively.

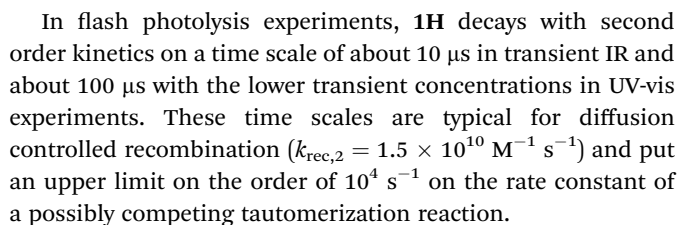
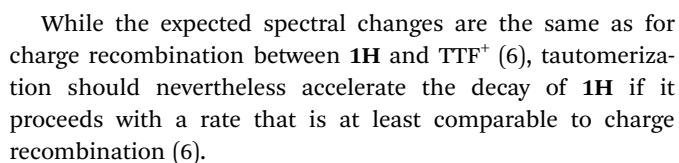
Notably, the protonation rate constant is almost two orders of magnitude below the diffusion controlled limit even for the strongly exergonic reaction with  $\text{Cl}_3\text{CCOOH}$  ( $\Delta pK_a = 3$ ). This is quite untypical for protonation of an amine base and indicative of significant reorganization associated with ligand protonation.

### Spectral comparison against the one-electron reduced hydride $\mathbf{4Hy}$

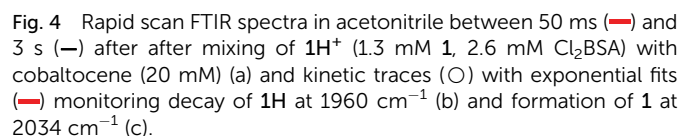
The above assignment of the protonation reaction to ligand protonation builds to a large extent on the general notion of nearly perfectly cancelling shifts in carbonyl frequencies caused by one-electron reduction and formation of a bridging hydride. This expectation could previously only be supported by the vanishing transient absorption observed upon protonation of complexes  $\mathbf{2}^-$  and  $\mathbf{3}^-$ .<sup>32,33</sup> Here, these assignments could be



According to the above arguments, also formation of a possibly more stable hydride **1Hy** by tautomerization (5) should lead to complete decay of all transient absorption given the predictable spectral similarity between **1** and **1Hy**.



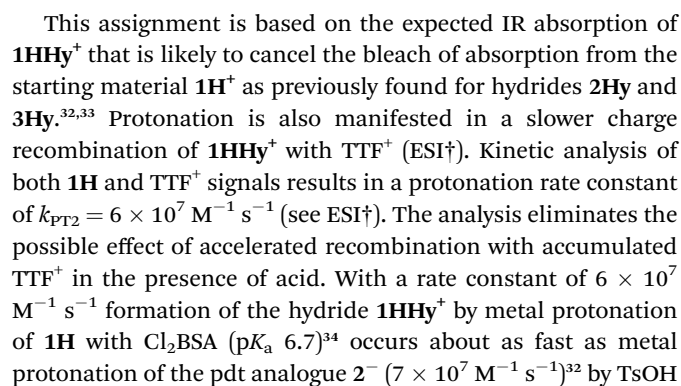
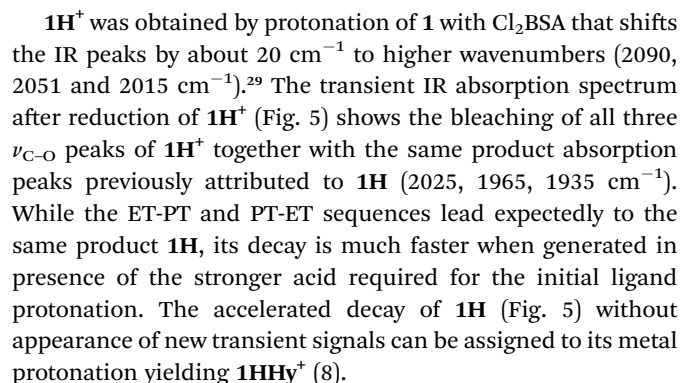
As a turnover frequency (TOF) of  $10^3$  to  $10^4$  s<sup>-1</sup> has been proposed from electrocatalytic experiments ( $\log(k_{\text{cat}}/\text{s}^{-1}) = 3.9$  and 2.6 for 6 mM Cl<sub>3</sub>CCOOH and ClH<sub>2</sub>CCOOH, respectively),<sup>27</sup> we wanted to probe the reactivity of **1H** on a longer time scale than 100  $\mu$ s. Thus, **1H**<sup>+</sup> was chemically reduced by cobaltocene in IR stopped flow experiments (rapid-scan FTIR). **1H**<sup>+</sup> was obtained by addition of two equivalents of 2,5-dichlorobenzenesulfonic acid (Cl<sub>2</sub>BSA, pK<sub>a</sub> = 6.7)<sup>34</sup> to warrant quantitative protonation of **1**. Reduction to **1H** occurred on a shorter time scale than the time resolution of the experiment. Importantly, **1H** was observed for several seconds (Fig. 4). Its decay with a lifetime of 1.3 s yields a product spectrum that can be assigned to the parent complex **1** or the tautomerization product **1Hy** given the expected similarity of their spectra. The former could be generated by catalytic turnover that leads to depletion of acid and therefore regenerates unreduced, unprotonated catalyst. Whether the slow decay of **1H** is predominantly due to turnover or tautomerization cannot be discriminated but the observed lifetime demonstrates in either case that the rate constant for tautomerization, if this occurs at all, has to be smaller than 1 s<sup>-1</sup>. We note that tautomerization

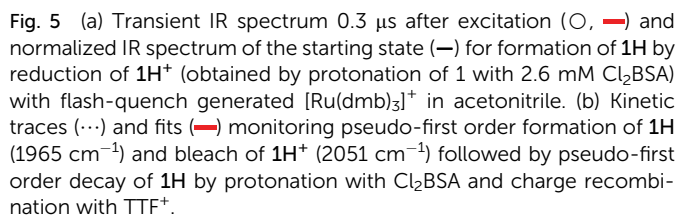


**Fig. 4** Rapid scan FTIR spectra in acetonitrile between 50 ms (—) and 3 s (—) after after mixing of **1H**<sup>+</sup> (1.3 mM **1**, 2.6 mM Cl<sub>2</sub>BSA) with cobaltocene (20 mM) (a) and kinetic traces (○) with exponential fits (—) monitoring decay of **1H** at 1960 cm<sup>-1</sup> (b) and formation of **1** at 2034 cm<sup>-1</sup> (c).

would be an intramolecular process that is independent on external conditions, such as identity and concentration of acid and the method of reduction (chemical or electrochemical).

Alternative formation of **1H** *via* the PT-ET route was studied by laser-flash induced reduction of **1H**<sup>+</sup> (7).





### Implications for (electro)catalytic H<sub>2</sub> formation

tautomerization, our results exclude however that a mechanism involving hydride formation by proton shuttling at the  $\text{Fe}_2(0,1)$  redox level could under any conditions result in the reported pseudo-first order catalytic rate constant on the order of  $10^3$  to  $10^4 \text{ s}^{-1}$ , as previously proposed.<sup>27</sup> It is important to note that the reported kinetics refer to the first catalytic wave ( $-1.4 \text{ V}$ ) that has been attributed to mechanisms where the hydride is formed prior to the second electron transfer, *i.e.* a CECE sequence with stronger acids or an ECCE sequence with weak acids. Therefore, possible formation of the hydride *via* tautomerization at the  $\text{Fe}_2(0,0)$  redox level ( $1\text{H}^- \rightarrow 1\text{Hy}^-$ ) cannot explain the superior catalytic performance of the adt complex.

An alternative advantage of the adt ligand might instead arise from the lowered barrier for hydride formation due to the structural changes at the iron core induced by the preceding ligand protonation. This notion would be in line with the relative sluggishness of the latter reaction (see above) and is corroborated by structural data that has been previously obtained from EXAFS spectra<sup>39</sup> of ligand- and metal-protonated states of the related Fe<sub>2</sub>(*l*,*l*) complex **4'**.<sup>¶37</sup> Specifically, protonation of the adt ligand in **4'** results in an elongated Fe–Fe bond distance in **4'H<sup>+</sup>** that is close to the distance found in the bridging hydride **4'HHy<sup>2+</sup>**. Formation of the hydride from the ligand protonated complex requires hence much less reorganization of this coordinate than formation of hydride **4'Hy<sup>+</sup>** from **4'**.

Generally, a proton shuttling ligand could accelerate not only the formation of the hydride intermediate but also its subsequent coupling with a proton. In case of adt complex **1**, with its bridging hydride intermediate, neither of the two steps is, however, likely to involve the adt-N, for steric reasons. In contrast to the terminal hydride of the enzyme active site, the hydride is bridging in the model complex (*cf.* Scheme 1), as evidenced by the conserved symmetry shown by the IR spectra, and the absence of a bridging CO IR band. The superior catalytic performance of **1** over its pdt analogue **2** is instead attributed to the observed acceleration of hydride formation with bulk acid as described above.

In summary, we could demonstrate by real-time spectroscopic observation that the initial protonation of hydrogenase model complex **1**, also in its one-electron reduced  $\text{Fe}_2(\text{l},0)$  state  $\mathbf{1}^-$  occurs on the adt ligand rather than the  $\text{Fe}_2$  core. The same ligand protonated intermediate **1H** was alternatively generated by one-electron reduction of  $\mathbf{1H}^+$  and no evidence for tautomerization of **1H** to a potentially more stable hydride **1Hy** was observed in either case. **1H** was stable on the time scale of 1 s, which shows that intramolecular proton shuttling cannot be responsible for the reported catalytic TOFs of  $10^3$  to  $10^4 \text{ s}^{-1}$ .<sup>27</sup> For catalytic  $\text{H}_2$  generation from weak acids this implies that no hydride intermediate is formed on the  $\text{Fe}_2(\text{l},0)$  level; instead, hydride formation may occur after further reduction, by direct protonation in the  $\text{Fe}_2(0,0)$  state. Only with strong acids a doubly protonated intermediate  $\mathbf{1HHy}^+$  is formed in the  $\text{Fe}_2(\text{l},0)$  state, by direct metal protonation of **1H**, not by ligand

protonation of a hydride precursor. Generally, it can therefore be concluded that, in contrast to the enzymatic reaction, the adt ligand of model complex **1** has no proton relay function that enables rapid formation of the bridging hydride intermediates on the Fe<sub>2</sub>( $\mu$ ,0) level. The protonation kinetics reveal however an exceptionally high barrier for protonation of the adt ligand that we suggest in turn may lower the barrier for hydride formation, presumably due to rearrangements of the metal core upon ligand protonation. In this way the basic site in the second coordination sphere might allow the catalyst to overcome the usual trade-off between overpotential and rate without invoking any proton-shuttling role.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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## Notes and references

¶ Protonation kinetics of the phosphine complexes **4** (ref. 29) and **4'** (ref. 37) have so far been studied only in the Fe<sub>2</sub>( $\mu_2$ ) state where hydride formation is extremely slow.

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