Controlling carbon monoxide binding at di-iron units related to the iron-only hydrogenase sub-site†

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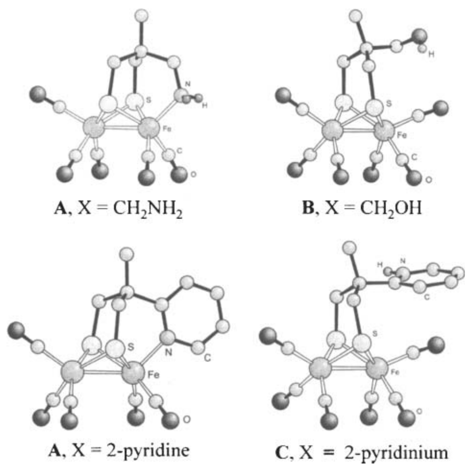
Carbon monoxide binding by displacement of a pendant hemi-labile ligand at a di-iron site can be substantially 'switched-on' *via* a ligand protonation pathway which is competitive with metal-metal bond protonation.

The binding of carbon monoxide to the resting and reduced states of the H-cluster of hydrogenase inhibits proton reduction/hydrogen oxidation by blocking the substrate binding site. This poisoning is reversible with enzyme activity restored by flushing out or pumping-off the CO.[1,2] In contrast, platinum electrocatalysts are far less robust to poisoning by trace CO and removal can only be effected by anodic oxidation of the adsorbate to CO_2 at high potentials.[3] Studies of the factors which control the formation of the substrate or inhibitor binding at di-iron units are thus of some relevance to both enzyme mechanism and to the design of new artificial electrocatalysts.

Here we report (i) the structures of new systems with pendant N or O groups ligating or proximal to a di-iron site which can bind CO, (ii) how the energetics of CO binding are controlled by the nature of the pendant groups, (iii) how protonation of the pendant group can trigger extensive CO binding and (iv) how protonation of the metal–metal bond is involved in an equilibration involving hydride-on/CO-off.

The N-ligated pentacarbonyl diiron complexes **A** (X = CH_2NH_2; X = 2-pyridine) are the first examples of this type of {NS2}-tripodal ligation at a dinuclear site, their structures are shown in Fig. 1. The thioether complexes used in this study were prepared as described earlier or by simple extension of the general method.[4] Illustrative syntheses, together with analytical and spectroscopic data are provided as ESI.†

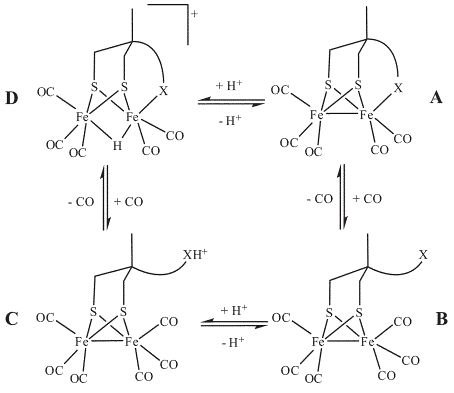
The complexes **A** possess more or less hemi-labile pendant N or S ligands (X) which can be replaced by CO to give complexes **B**, Scheme 1. We have measured the equilibrium constant K_{eq} at 293 K for this reversible binding of CO and the data are given in Table 1. Table 1 shows that for the thioether series the equilibrium position is dominated by electronic effects of the pendant group. As an example, the electron-withdrawing *p*-cyanobenzene group favours CO binding by about two orders of magnitude over that of the benzyl thioether derivative (Table 1, entries 2 and 7). Behaviour at the two equilibrium extremes is displayed by complexes with pendant CH_2NH_2 and CH_2OH groups: the equilibrium concentration of the pentacarbonyl **A** (X = CH_2OH) is below the detection limit in the FTIR experiment (1%) and we were not able to effect the conversion of **B** (X = CH_2OH) to **A** (X = CH_2OH) by refluxing in toluene under dinitrogen; conversely, the equilibrium concentration of the hexacarbonyl **B** (X = CH_2NH_2) is below the detection limit under CO at one atmosphere. Fig. 1 shows the X-ray crystal structures of the amine, pyridine and alcohol complexes.



A, X = CH_2NH_2 **B**, X = CH_2OH

A, X = 2-pyridine **C**, X = 2-pyridinium

Fig. 1 Views of representative X-ray crystallographic structures illustrating 'closed' **A**, 'open' **B** and protonated **C** forms of the di-iron units.‡



Scheme 1 Interconversions involving hemi-labile ligands, protons and carbon monoxide at di-iron dithiolate units.

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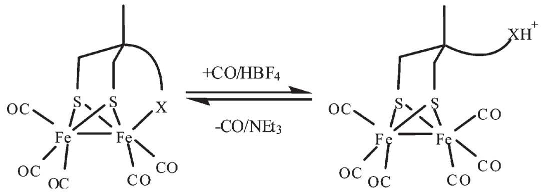
Table 1 Equilibrium constants and estimated standard free energies for binding of CO to **A**

Entry	Complex	K_{eq} (L mol^{-1})	ΔG°_{293} (kJ mol^{-1})
0	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]^a$ (X = CH_2OH)	$>10^3$	<-17
1	$[Fe_2(CO)_4(CN)\{CH_3C(CH_2S)_2X\}]^{1-}$ (X = CH_2SCH_3)	625 ± 5	−15.68 ± 0.02
2	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = $CH_2SC_6H_4$-*p*-CN)	453 ± 11	−14.9 ± 0.1
3	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = $CH_2SC_6H_4$-*p*-NO_2)	362 ± 28	−14.4 ± 0.2
4	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = $CH_2SC_6H_4$-*p*-NH_3^+)	125 ± 19	−11.8 ± 0.4
5	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = $CH_2SC_6H_4$-*p*-NH_2)	13.7 ± 0.1	−6.38 ± 0.02
6	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = 2-pyridine)	3.6 ± 0.1	−3.1 ± 0.1
7	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2CH_2X\}]$ (X = $SCH_2C_6H_5$)	3.2 ± 0.3	−2.8 ± 0.2
8	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = CH_2SCH_3)	$<10^0$	>0
9	$[Fe_2(CO)_5\{CH_3C(CH_2S)_2X\}]$ (X = CH_2NH_2)	$<10^0$	>0

[a] Hexacarbonyl present in >99% concentration.

'Remote' protonation can switch the donicity of the pendant group, X. For example, the conversion of the *p*-aniline group to the *p*-anilinium cation increases the equilibrium constant in favour of CO binding by an order of magnitude. This is undoubtedly a consequence of decreasing the Fe–$S_{thioether}$ bond enthalpy, Table 1 (entries 5 and 4).

Addition of the acid $HBF_4 \cdot Et_2O$ to **A** (X = CH_2NH_2; 2-pyridine) under CO (1 atm.; rt; CH_2Cl_2) results in the rapid formation of the hexacarbonyl with concomitant de-coordination of the N-ligands as the pendant ammonium and pyridinium salts respectively, Eqn (1). Monitoring the reactions by FTIR shows that under CO the addition of 1 equivalent of the acid results in an infra-red pattern in the carbonyl region essentially identical to that of $[Fe_2\{S(CH_2)_3S\}(CO)_6]^6$ for **A** (X = CH_2NH_2; X = 2-pyridine), Fig. 2. The overall reversibility of the process is illustrated by addition of base (triethylamine) which quantitatively restores the spectrum of the parent species, Fig. 2. The proton switched CO coordination was fully confirmed by isolation of **C** (X = 2-pyridinium) and X-ray crystallographic determination of its structure, Fig. 1.



(1)

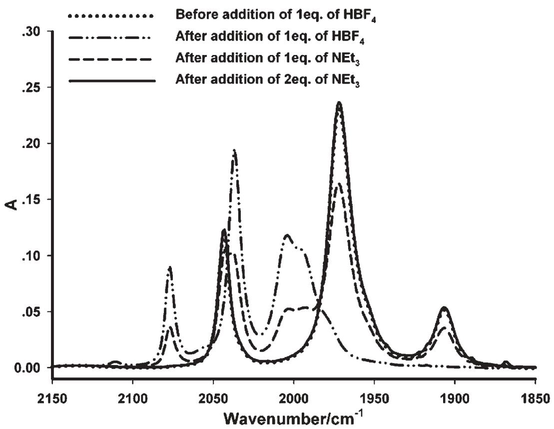


Fig. 2 FTIR spectral changes for complex **A** (X = CH_2NH_2) upon protonation/de-protonation in MeCN under CO (1 atm.) at 293 K.

Addition of the acid to **A** (X = CH_2SMe) under CO does not lead to the formation of **B** (X = CH_2SHMe^+), rather it results in protonation of the metal–metal bond to give the bridging hydride **D**, Scheme 1. The evidence for this is as follows: Fig. 3 (a) shows the FTIR of **A** (X = CH_2SMe) before and after reaction with excess $HBF_4 \cdot Et_2O$. First, the infra-red spectral pattern after the reaction is essentially identical to that before protonation except

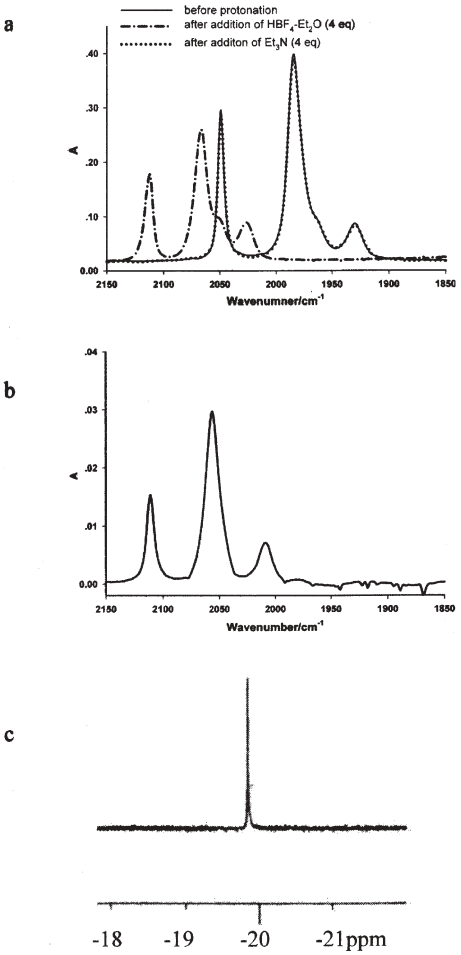


Fig. 3 Bridging hydride formation (a) reversible protonation of the metal–metal bond of complex **A** (X = CH_2SMe) in dichloromethane giving **D** (X = CH_2SMe) (b) FTIR of hydride component **D** (X = CH_2NH_2) and (c) ^1H NMR spectrum of **D** (X = CH_2SMe) showing the hydride resonance.

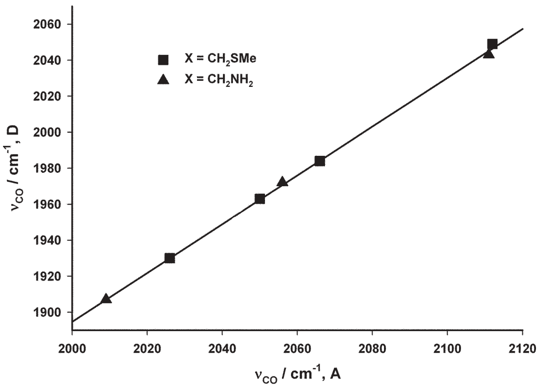


Fig. 4 Experimental ν(CO) for the hydrides **D** (X = CH_2SMe, CH_2NH_2) *versus* ν(CO) for the conjugate bases **A** (X = CH_2SMe, CH_2NH_2).

that all peaks are shifted by 80 ± 17 cm^{-1} to higher frequencies; this is indicative of retention of the basic structure of the complex. Secondly, de-protonation fully restores the spectrum of the parent compound, thus the observed shift to higher frequencies on protonation cannot be a consequence of oxidation. Thirdly, ^1H NMR (CD_2Cl_2) unequivocally shows a single peak at −19.8 ppm, consistent with the formation of a bridging hydride, Fig. 3 (c).[7] Notably, **D** provides the first example of a hydride at an enzymatically relevant {2Fe3S} core.

A closer inspection of the infra-red spectrum of A (X = CH_2NH_2) following protonation under CO shows additional bands with low intensity, Fig. 2. These bands are enhanced when the protonation is carried out under dinitrogen, but the species formed slowly decays.§ The resolved infra-red pattern closely matches that of the hydride **D** (X = SMe), Fig. 3 (b), indicative of the formation of **D** (X = CH_2NH_2). Convincingly, we find that the plot of ν(CO) for the protonated **D** (X = CH_2SMe, CH_2NH_2) *versus* non-protonated **A** (X = CH_2SMe, CH_2NH_2) pairs shows an extraordinary linearity (correlation coefficient, r = 0.9996), Fig. 4. This unambiguously supports structurally analogous protonations, *i.e* bridging hydride formation. In a wider context this type of correlation may serve in the identification of the retention of overall structural geometry before and after protonation.

Finally, we briefly consider the intimate pathways by which the equilibria involving **A–D** take place. In the absence of acid, dissociation of X from the metal centre could provide a vacant site at which CO can bind. In the presence of acid the trapping of this dissociated X group as XH^+ would diminish the rate of the back reaction by both lowering the effective concentration of free X and the nucleophilicity of the incoming group, XH^+, thus favouring carbonylation. However, in earlier work we have shown that associative pathways operate in the substitution of CO or X groups, as in the conversion of $[Fe_2(CO)_4(CN)\{CH_3C(CH_2S)_2CH_2SCH_3\}]^{1-}$ to the hexacarbonyl (Table 1, entry 1).[5] Thus it is the formation of a bridging CO transition state with the loss of the Fe–Fe bond, in concert with associative attack, which provides a low activation energy pathway for subsitution of X by CO (or the converse), and this circumvents the need for high energy 20-electron intermediates. Trapping the dissociated X group with H^+ could of course operate *via* this associative pathway, but here again some circumspection is needed. It is clear that with ligated X = CH_2NH_2 or CH_2SMe the Fe–Fe bond is sufficiently basic to be extensively protonated. The positive charge brought in would reasonably be expected to both strengthen the Fe–X bond and lower the tendency for electrophilic attack by CO. Just as bridging and terminal CO switching can provide a low activation energy for substititution, so it may be that migration or tunneling of a proton from the bridging mode to the Fe–N bond allows concerted associative attack by CO and dissociation of XH^+.

In summary, we have demonstrated how the nature of a pendant 'hemi-labile' ligand can control the extent of carbonylation of a di-iron unit and how this can be further modified by protonation reactions, including equilibration between hydride-on/CO-off. The nature of X both as a base and as a ligand, and the influence it has on the basicity of the metal–metal bond, provides control of the ligand hemi-lability and activity of the di-iron unit and this is relevant to catalyst design.

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Notes and references

‡ CCDC 658089–658093. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b712805c

§ The complex **A** (X = CH_2NH_2) reacts with the acid in the absence of CO to give initially strong bands of the hydride at 2111, 2056 and 2009 cm^{-1} that decay with the formation of the hexacarbonyl that must be formed by the scavenging of CO from (oxidised) material. The complex **A** (X = 2-pyridine) reacts with $HBF_4{\cdot}Et_2O$ in the absence of CO in a similar fashion. Notably solvato-adducts are not formed.

1 B. Bennett, B. J. Lemon and J. W. Peters, *Biochemistry*, 2000, **39**, 7455–7460.

2 W. Roseboom, A. L. De Lacey, V. M. Fernandez, E. C. Hatchikian and S. P. J. Albracht, *JBIC, J. Biol. Inorg. Chem.*, 2006, **11**, 102–118.

3 D. S. Corringan and M. J. Weaver, *J. Electroanal. Chem.*, 1988, **241**, 143–162.

4 S. K. Ibrahim, X. Liu, C. Tard and J. Pickett Christopher, *Chem. Commun.*, 2007, 1535–1537; C. Tard, X. Liu, S. K. Ibrahim, M. Bruschi, L. De Gioia, S. Davies, X. Yang, L.-S. Wang and C. J. Pickett, *Nature*, 2005, **433**, 610–613; X. Liu, S. K. Ibrahim, C. Tard and C. J. Pickett, *Coord. Chem. Rev.*, 2005, **249**, 1641–1652; D. J. Evans and C. J. Pickett, *Chem. Soc. Rev.*, 2003, **32**, 268–275; M. Razavet, S. C. Davies, D. L. Hughes, J. E. Barclay, D. J. Evans, S. A. Fairhurst, X. Liu and C. J. Pickett, *Dalton Trans.*, 2003, 586–595.

5 S. J. George, Z. Cui, M. Razavet and C. J. Pickett, *Chem.–Eur. J.*, 2002, **8**, 4037–4046.

6 S. J. Borg, T. Behrsing, S. P. Best, M. Razavet, X. Liu and C. J. Pickett, *J. Am. Chem. Soc.*, 2004, **126**, 16988–16999.

7 S. Ezzaher, J.-F. Capon, F. Gloaguen, F. Y. Pétillon, P. Schollhammer and J. Talarmin, *Inorg. Chem.*, 2007, **46**, 3426–3428; W. Dong, M. Wang, X. Liu, K. Jin, G. Li, F. Wang and L. Sun, *Chem. Commun.*, 2006, 305–307; L. Schwartz, G. Eilers, L. Eriksson, A. Gogoll, R. Lomoth and S. Ott, *Chem. Commun.*, 2005, 520–522; F. Gloaguen, J. D. Lawrence, T. B. Rauchfuss, M. Bénard and M.-M. Rohmer, *Inorg. Chem.*, 2002, **41**, 6573–6582; J. I. van der Vlugt, T. B. Rauchfuss, C. M. Whaley and S. R. Wilson, *J. Am. Chem. Soc.*, 2005, **127**, 16012–16013; J. L. Nehring and D. M. Heinekey, *Inorg. Chem.*, 2003, **42**, 4288–4292; X. Zhao, I. P. Georgakaki, M. L. Miller, R. Mejia-Rodriguez, C.-Y. Chiang and M. Y. Darensbourg, *Inorg. Chem.*, 2002, **41**, 3917–3928.