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A di-iron dithiolate possessing structural elements of the carbonyl/cyanide sub-site of the H-centre of Fe-only hydrogenase

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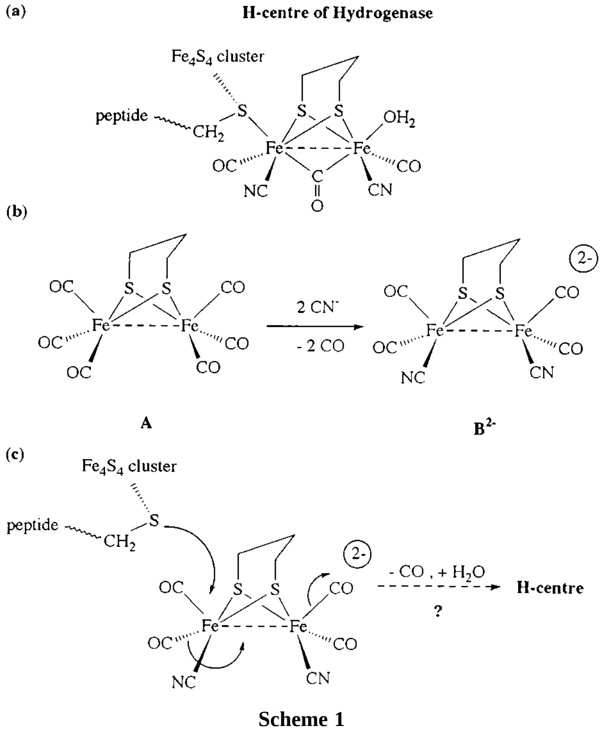
The synthesis and characterisation of the first {2Fe2S}-cluster bearing both CO and CN ligands is described; the iron atoms are linked by the bridging 1,3-propanedithiolate unit that has been identified in the crystallographic structure of the {2Fe2S} sub-unit of the H-centre of the all-iron hydrogenase from *Desulfovibrio desulfuricans*.

Two recent X-ray crystallographic structures of Fe-only hydrogenases isolated from *Desulfovibrio desulfuricans*[1] and *Clostridium pasteurianum*[2] show that the H-centre, the active site at which protons are reduced to dihydrogen, is comprised of a conventional {4Fe4S}-cluster linked by a bridging cysteinyl ligand to an extraordinary 'organometallic' di-iron sub-site. The combined structural data, taken together with FTIR data obtained for the Fe-only hydrogenase from *Desulfovibrio vulgaris*,[3] strongly suggest that the sub-site is ligated by terminal CO and CN molecules with the two iron atoms linked by a 1,3-propanedithiolate ligand and bridged by a carbonyl group; the *exo* Fe atom is either coordinatively unsaturated[1] or is ligated with a water molecule[2] [Scheme 1(a)].

We now report the synthesis and characterisation of the first dinuclear iron–sulfur complex with both CO and CN ligation at the iron atoms. Importantly, this dianion also possesses the bridging propanedithiolate structural motif identified in the higher resolution protein X-ray structure.[1]

The known di-iron complex [(CO)$_3$FeSCH$_2$CH$_2$CH$_2$S-Fe(CO)$_3$] **A**[4] reacts with 2 equivalents of NEt$_4$CN in MeCN at room temperature to give the dianionic salt [NEt$_4$]$_2$[(CO)$_2$-(NC)FeSCH$_2$CH$_2$CH$_2$SFe(CN)(CO)$_2$], {[NEt$_4$]$_2$**B**}, essentially quantitatively. [NEt$_4$]$_2$**B** was isolated as an orange, air-sensitive, crystalline material [Scheme 1(b)].



Scheme 1

^{1}H, ^{13}C{^{1}H} NMR and Mössbauer spectroscopy are consistent with the formulation of [NEt$_4$]$_2$**B** and indicate an arrangement in the dianion with two CO ligands and one CN ligand at each Fe centre. The Mössbauer spectrum displays a well defined doublet with isomer shift and quadrupole splitting parameters similar to those of the parent hexacarbonyl and related molecules with sulfur bridging two metal–metal bonded Fe$^{\mathrm{I}}$ atoms.† FTIR spectra (NEt$_4^+$ salt, MeCN solution) show ν(CO) 1964s 1922s 1885s and 1871sh cm^{-1} with ν(CN) at 2075m cm^{-1}. The ^{13}CN-labelled salt [18-crown-6·K]$_2$**B** shows ν(^{13}CN) at 2031 cm^{-1}; the shift in frequency of 44 cm^{-1} from that of the ^{12}CN complex is close to that theoretically expected (43 cm^{-1}). The ν(CO) stretches are not shifted in the labelled complex, this shows that the CN oscillator(s) is not coupled with CO. In addition, the solution FTIR spectrum of the mixed labelled complex shows no additional absorptions which would be indicative of coupling between the two CN ligands.

X-Ray crystallographic analysis of an incomplete, low-angle diffraction data-set confirms the skeletal arrangement of the dianion **B**$^{2-}$, *viz.* two iron atoms bridged by the 1,3-propanedithiolate ligand, with dimensions very close to those observed for the sub-unit in the enzyme,[1] and three further ligands (CO/CN) attached to each Fe atom.‡

Normal coordinate analysis, using a Cotton–Kraihanzel force field,[6,7] of the CO IR data shows that the pattern of ν(CO) bands is consistent with the dianion possessing pseudo-C_s symmetry with eclipsed CN ligands as represented in Scheme 1(b).

Given the general robustness of {Fe$_2$S$_2$(CO)$_6$} units, it is somewhat surprising that substitution occurs under such mild conditions.[5] The reaction is not confined to **A** but occurs with other dithiolate-bridged di-iron hexacarbonyl clusters, for example, we have synthesised and characterised the bridge-functionalised complex [NEt$_4$]$_2$[(CO)$_2$(NC)FeSCH$_2$CH-(CH$_2$OH)SFe(CN)(CO)$_2$], {[NEt$_4$]$_2$**C**} from the corresponding hexacarbonyl precursor.†

Primary (irreversible) reduction of the dianion **B**$^{2-}$ occurs at $E_\mathrm{p}^\mathrm{red} = -2.33$ V *vs.* SCE and primary (irreversible) oxidation occurs at $E_\mathrm{p}^\mathrm{ox} = -0.11$ V *vs.* SCE {recorded in MeCN–0.1 M NBu$_4$BF$_4$ at vitreous carbon, 100 mV s^{-1}, room temp.}. **B**$^{2-}$ is both stable and *very* soluble in water as the [NEt$_4$]$^+$ salt, although it neither reacts with nor electrocatalyses the reduction of protons in aqueous solution over the pH range 8.4–4.0. Why **B**$^{2-}$ does not effect the reduction of protons, whereas the sub-unit of the H-centre does so, is probably linked to the relative electron-richness of the 2Fe2S units. With respect to the synthetic cluster, the enzyme sub-unit has a bridging cysteinyl group formally displacing an electron-withdrawing terminal CO ligand into a bridging mode and also a CO ligand formally replaced by a donor water molecule [Scheme 1(c)]. We thus predict that the enzymic sub-unit would be oxidised at a potential substantially negative of that of **B**$^{2-}$ and sufficient to drive proton reduction at modest pH. That $\mathbf{B}^{2-}$ is both highly water soluble and stable over a wide range of pH suggests that it could be involved in the cellular biosynthesis of the H-centre [Scheme 1(c)].

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Note added in proof: We thank Professor J. W. Peters for a pre-print of an X-ray crystallographic study of the CO inhibited form of the Fe hydrogenase from *C. pasteurianum.* This shows CO replaces coordinated H_2O at the distal iron atom of the H-centre 2Fe2S sub-unit *cf.* the inability of $\mathbf{B}^{2-}$ to catalyse proton reduction.

Notes and references

† $[\mathrm{NEt_4}]_2\mathbf{B}$: ^{1}H NMR (400 MHz, $\mathrm{CD_3CN}$): δ 1.20 [24H, br, $(\mathrm{C}\mathit{H}_3\mathrm{CH_2})_4\mathrm{N}^+$], 1.63 (2H, br, $\mathrm{SCH_2C}\mathit{H}_2\mathrm{CH_2S}$), 1.81 (4H, br, $\mathrm{SC}\mathit{H}_2\mathrm{CH_2C}\mathit{H}_2\mathrm{S}$), 3.17 [16H, br, $(\mathrm{CH_3C}\mathit{H}_2)_4\mathrm{N}^+$]; ^{13}C{^{1}H} NMR (100 MHz, $\mathrm{CD_3CN}$): δ 7.9 [$(\mathit{C}\mathrm{H_3CH_2})_4\mathrm{N}^+$], 23.6 ($\mathrm{S}\mathit{C}\mathrm{H_2CH_2}\mathit{C}\mathrm{H_2S}$), 31.3 ($\mathrm{SCH_2}\mathit{C}\mathrm{H_2CH_2S}$), 53.2 [$(\mathrm{CH_3}\mathit{C}\mathrm{H_2})_4\mathrm{N}^+$], 151.2 (CN), 220.6 (CO). Mössbauer spectrum (solid, 77 K, referenced to 25 μm Fe-foil at 298 K): doublet; isomer shift +0.05 mm s^{-1}; quadrupole splitting 1.03 mm s^{-1}. See: *The Organic Chemistry of Iron*, ed. E. A. Koerner von Gustorf, F. W. Grevels and I. Fischler, Academic Press, New York, 1978, vol. 1, pp. 175–211. FTIR (in MeCN): [18-crown-6·K]$_2$**B**: ν(CO) 1871 (sh), 1883s, 1921s, 1963s and ν(CN) 2075m cm^{-1}; ^{13}CN-labelled [18-crown-6·K]$_2$**B**: ν(CO) 1871 (sh), 1883s, 1921s, 1961s and ν(^{13}CN) 2031m cm^{-1}. FABMS: *m/z* 772 $\{[\mathrm{NEt_4}]_3\mathrm{M}\}^+$, 586 $\{[\mathrm{NEt_4}]_2\mathrm{M} - 2\mathrm{CO}\}^+$, 530 $\{[\mathrm{NEt_4}]_2\mathrm{M} - 4\mathrm{CO}\}^+$, 457 $\{[\mathrm{NEt_4}]\mathrm{MH} - 2\mathrm{CO}\}^+$, 414 $\{[\mathrm{NEt_4}][\mathrm{Fe_2S_2(CN)_2(CO)_2}]\}^+$, 413 $\{[\mathrm{NEt_4}][\mathrm{Fe_2S(CNH)(CO)_4}]\}^+$, 307 $\{[\mathrm{NEt_4}]\mathrm{Fe_2S_2H}\}^+$, 157 $\{[\mathrm{NEt_4}]\mathrm{CNH}\}^+$, 130 $[\mathrm{NEt_4}]^+$. Microanalysis: $\mathrm{C_{25}H_{46}Fe_2N_4O_4S_2\cdot H_2O}$, found (calc.): C, 46.1(45.5); H, 7.95(7.32); N, 8.5(8.5); S, 9.0(9.7); Fe 15.8 (16.7%).

$[\mathrm{NEt_4}]_2\mathbf{C}$: ^{1}H NMR (400 MHz, $\mathrm{CD_3CN}$): δ 1.23 [24H, br, $(\mathrm{C}\mathit{H}_3\mathrm{CH_2})_4\mathrm{N}^+$], 1.55 [1H, dd, ^2J 9, ^3J 6 Hz, $\mathrm{SC}\mathit{H}\mathrm{HCH(CH_2OH)S}$], 2.22 [2H, m, $\mathrm{SCH}\mathit{H}\mathrm{CH(CH_2OH)S}$ and $\mathrm{SCH_2C}\mathit{H}\mathrm{(CH_2OH)S}$], 2.44 (1H, t, ^3J 5.5 Hz, OH), 3.20 [16H, br, $(\mathrm{CH_3C}\mathit{H}_2)_4\mathrm{N}^+$], 3.36 (1H, dd, ^2J 8.5, ^3J 6.5 Hz, $\mathrm{C}\mathit{H}\mathrm{HOH}$), 3.47 (1H, dd, ^2J 8.5, ^3J 7 Hz, $\mathrm{CH}\mathit{H}\mathrm{OH}$); ^{13}C{^{1}H} NMR (100 MHz, $\mathrm{CD_3CN}$): δ 7.7 [$(\mathit{C}\mathrm{H_3CH_2})_4\mathrm{N}^+$], 37.0 and 54.3 [$\mathrm{SCH_2CH(CH_2OH)S}$], 66.1 ($\mathrm{CH_2OH}$), 53.0 [$(\mathrm{CH_3}\mathit{C}\mathrm{H_2})_4\mathrm{N}^+$], 66.1 ($\mathrm{CH_2OH}$), 149.2 (CN), 221.4 (CO). Mössbauer spectrum (solid, 77 K, referenced to 25 μm Fe-foil at 298 K): doublet; isomer shift 0.03 mm s^{-1}; quadrupole splitting 1.09 mm s^{-1}. FTIR (in MeCN): ν(CO) 1874 (sh), 1888s, 1924s, 1966s and ν(CN) 2032w and 2076m cm^{-1}. Microanalysis: $\mathrm{C_{25}H_{46}Fe_2N_4O_5S_2\cdot 0.5\,Et_2O}$, found (calc.: C, 46.8(46.6); H, 7.47(7.39); N, 8.1(8.1); S, 8.9(9.2); Fe, 15.6(16.1%).

‡ The overall geometry of the anion is well established. The $\mathrm{Fe_2}$(dithiolate) core is well resolved and shows reasonable molecular dimensions, *e.g.* the four Fe–S bonds lie in the range 2.251(17)–2.318(17) Å, mean 2.276(14) Å, and the Fe–Fe distance is 2.528(11) Å. The two S–C bond lengths are 1.87(5) and 1.84(5) Å and the bridging C–C lengths are each 1.60(6) Å. Each iron is five coordinate with a square pyramidal geometry (octahedral coordination completed by a bent Fe–Fe bond[5]).

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