

Synthesis and structure of a thiolate-bridged nickel–iron complex: towards a mimic of the active site of NiFe-hydrogenase

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The reaction, under carbon monoxide, of $[\text{Fe}(\text{NS}_3)(\text{CO})]^-$ [$\text{NS}_3 = \text{N}(\text{CH}_2\text{CH}_2\text{S})_3^{3-}$] with $[\text{NiCl}_2(\text{dppe})]$ gives the structurally characterised dinuclear thiolate-bridged complex $[\{\text{Fe}(\text{NS}_3)(\text{CO})_2\text{-S,S'}\}\text{NiCl}(\text{dppe})]$, which has structural features similar to those of the active site of NiFe-hydrogenase.

Hydrogenases catalyse the reversible reduction of protons to dihydrogen. The NiFe-hydrogenase from *Desulfovibrio gigas*, as aerobically isolated in the inactive form, has been characterised recently by X-ray crystallography.^{1,2} This indicates that the active site is most likely a dinuclear thiolate-bridged nickel–iron complex in which the nickel atom is coordinated by four cysteinyl-sulfur atoms, two of which bridge to a six-coordinate iron atom. In the aerobically isolated crystals there is an additional bridging feature, probably oxo or hydroxo, which is unlikely to be present in the active form of the enzyme.^{2,3} The other ligands to iron, as shown by crystallography and spectroscopy,² are, unusually for biology, two cyanides and one carbon monoxide. There are no examples in the chemical literature of synthetic analogues with bis(thiolate-bridged) nickel to iron with carbon monoxide bound to the iron atom, although $[\{\text{NiL-S}\}\text{Fe}(\text{CO})_4]$ [$\text{H}_2\text{L} = N,N'$ -bis(ethanethiol)-1,5-diazacyclooctane]⁴ and $[\{\text{NiL}'\text{-S,S'}\}\text{Fe}(\text{NO})_2]$ ($\text{H}_2\text{L}' = N,N'$ -diethyl-3,7-diazanonane-1,9-dithiolate)⁵ have one or other of these features. In this work we have employed the complex $[\text{Fe}(\text{NS}_3)(\text{CO})]^-$ as a chelate ligand to nickel to prepare a bis(thiolate-bridged) nickel–iron complex which has both of these structural features and has similarities to the active site of NiFe-hydrogenase.

The reaction, under a CO atmosphere, of $[\text{NiCl}_2(\text{dppe})]$ with $[\text{NET}_4][\text{Fe}(\text{NS}_3)(\text{CO})]$ gives the dinuclear complex $[\{\text{Fe}(\text{NS}_3)(\text{CO})_2\text{-S,S'}\}\text{NiCl}(\text{dppe})]$ **1**,[†] the structure of which is shown in Fig. 1.[‡] The iron atom is octahedrally coordinated,

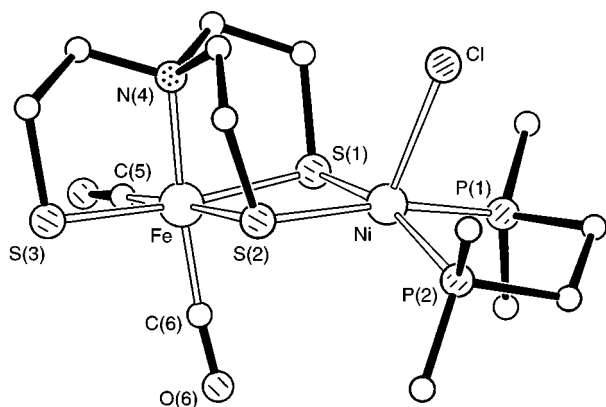


Fig. 1 A molecule of $[\{\text{Fe}(\text{NS}_3)(\text{CO})_2\text{-S,S'}\}\text{NiCl}(\text{dppe})]$ **1** showing the principal atoms. The phenyl groups of the dppe ligand have been omitted for clarity. Selected distances (Å) and angles ($^\circ$): Fe–S(1) 2.281(3), Fe–S(2) 2.331(3), Fe–S(3) 2.306(3), Fe–N(4) 2.031(8), Fe–C(5) 1.783(12), Fe–C(6) 1.741(10), Ni–Fe 3.308(2), Ni–S(1) 2.247(3), Ni–S(2) 2.255(3), Ni–P(1) 2.164(3), Ni–P(2) 2.196(3), Ni–Cl 2.508(3); S(1)–Fe–S(2) 85.2(1), S(1)–Ni–S(2) 87.8(1), Fe–S(1)–Ni 93.9(1), Fe–S(2)–Ni 92.3(1).

with two of the thiolate ligand arms also bridging to the nickel atom. The Ni is five-coordinate in a square pyramidal pattern in which the Ni atom is displaced 0.307(2) Å from the base plane towards the chloride ligand in the apical site. The normals to the S_3C 'equatorial' plane about the Fe atom and the P_2S_2 base plane about the Ni atom are inclined at $19.4(1)^\circ$. The NS_3 ligand arrangement is different from those reported previously^{6,7} in trigonal bipyramidal complexes of iron and vanadium, where there is approximate threefold symmetry in the ligand. Here, the three thiolate sulfur atoms are arranged meridionally about the Fe and the pair of mutually *trans* thiolate arms of the ligand are essentially mirror images (with opposite S–C–N torsion angles). The carbonyl ligands are opposite the amino nitrogen atom and one of the bridging sulfur atoms.

Complex **1** is a good structural analogue of the proposed active site of NiFe-hydrogenase, Fig 2. The core of **1** is dinuclear with nickel bound to iron by a bis(thiolate-bridge) and the iron atom binds two carbon monoxides. The Ni...Fe distance of 3.308 Å is similar to those found for other thiolate-bridged nickel complexes (2.80–3.76 Å^{4,5,8–10}) but is longer than the Ni...Fe distance, 2.9 Å, in the as isolated, inactive NiFe-hydrogenase.^{1,2} However, recent theoretical calculations predict that in the active states of the enzyme the Ni...Fe distance is > 2.9 Å.³

The C–O stretching frequencies in the IR spectrum of **1** are at 1944 and 2000 cm^{-1} . The 1944 cm^{-1} feature is assigned to the axial CO and appears at a similar position to the axial CO stretch in the trinuclear complexes $[\text{M}\{\text{Fe}(\text{NS}_3)(\text{CO})\text{-S,S'}\}_2]$ [$\text{M} = \text{Fe}$ (1937 cm^{-1});⁶ Co (1937 cm^{-1});¹¹ Ni (1934 cm^{-1})¹¹] and to the CO band (1947 cm^{-1}) for the inactive form of *D. gigas* NiFe-hydrogenase.² Mössbauer parameters at 77 K (rel. natural Fe at 298 K) are: isomer shift (IS) 0.07 mm s^{-1} and quadrupole splitting (QS) 0.56 mm s^{-1} , consistent with octahedral low-spin iron(II). When the synthesis is performed under dinitrogen or argon, rather than CO, a complex **2**, probably a mono-CO complex, is formed with a carbonyl stretch at 1903 cm^{-1} and Mössbauer parameters of IS 0.23 mm s^{-1} and QS 0.40 mm s^{-1} . When an acetonitrile solution of **2** is stirred under a CO atmosphere it is converted to the dicarbonyl complex **1**.

The potential catalytic properties of the complex **1** will be investigated in the future.

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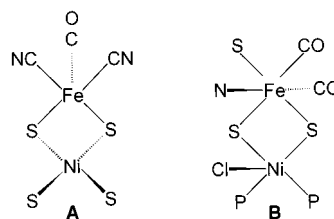


Fig. 2 A schematic comparison of the proposed enzyme active site (A) and the core of complex **1** (B).

Notes and references

† Under an atmosphere of carbon monoxide, to a stirred suspension of $[\text{NiCl}_2(\text{dpe})]$ (0.79 g, 1.5 mmol) in MeCN (100 cm³) was added a solution of $[\text{NEt}_4][\text{Fe}(\text{NS}_3)(\text{CO})]$ in MeCN (20 cm³). Dissolution was complete after 30 min. On standing overnight a dark brown, crystalline product was obtained, which was collected by filtration, washed with diethyl ether and dried (0.99 g, 83%). Found: C, 50.8; H, 4.3; N, 2.2; Fe, 6.2; Ni, 7.5. $\text{C}_{34}\text{H}_{36}\text{ClFeNNiO}_2\text{P}_2\text{S}_3$ requires: C, 51.1; H, 4.5; N, 1.8; Fe, 7.0; Ni, 7.4%. $\lambda_{\text{max}}/\text{nm}$ ($\epsilon/\text{dm}^3 \text{mol}^{-1} \text{cm}^{-1}$) (CH_2Cl_2) 325 (18831), 494 (2614).

‡ *Crystal data:* $\text{C}_{34}\text{H}_{36}\text{ClFeNNiO}_2\text{P}_2\text{S}_3$, $M = 798.8$, triclinic, space group $P1$ (no. 2), $a = 11.5630(11)$, $b = 12.068(2)$, $c = 12.348(2)$ Å, $\alpha = 91.563(13)$, $\beta = 91.289(10)$, $\gamma = 92.839(10)^\circ$, $V = 1719.9(4)$ Å³. $Z = 2$, $D_c = 1.54 \text{ g cm}^{-3}$, $F(000) = 824$, $T = 293 \text{ K}$, $\mu(\text{Mo-K}\alpha) = 1.36 \text{ mm}^{-1}$, $\lambda(\text{Mo-K}\alpha) = 0.71069$ Å. 4782 Unique reflections were measured to $\theta_{\text{max}} 23^\circ$ (2254 with $I > 2\sigma$). Structure determined by direct methods in SHELXS,¹² refined with all data, on F^2 , in SHELXL¹³ to $wR_2 = 0.151$; for the 'observed' data, $R_1 = 0.058$.

CCDC 182/1390. See <http://www.rsc.org/suppdata/cc/1999/1935/> for crystallographic files in .cif format

- 1 A. Volbeda, M.-H. Charon, C. Piras, E. C. Hatchikian, M. Frey and J. C. Fontecilla-Camps, *Nature*, 1995, **373**, 580.
- 2 A. Volbeda, E. Garcin, C. Piras, A. L. de Lacey, V. M. Fernandez, E. C. Hatchikian, M. Frey and J. C. Fontecilla-Camps, *J. Am. Chem. Soc.*, 1996, **118**, 12 989.

- 3 S. Niu, L. M. Thomson and M. B. Hall, *J. Am. Chem. Soc.*, 1999, **121**, 4000; L. De Gioia, P. Fantucci, B. Guigliarelli and P. Bertrand, *Inorg. Chem.*, 1999, **38**, 2658; P. Amara, A. Volbeda, J. C. Fontecilla-Camps and M. J. Field, *J. Am. Chem. Soc.*, 1999, **121**, 4468.
- 4 C.-H. Lai, J. H. Reibenspies and M. Y. Darensbourg, *Angew. Chem., Int. Ed. Engl.*, 1996, **35**, 2390.
- 5 F. Osterloh, W. Saak, D. Haase and S. Pohl, *Chem. Commun.*, 1997, 979.
- 6 S. C. Davies, D. L. Hughes, R. L. Richards and J. R. Sanders, *Chem. Commun.*, 1998, 2699.
- 7 S. C. Davies, D. L. Hughes, Z. Janas, L. Jerzykiewicz, R. L. Richards, J. R. Sanders and P. Sobota, *Chem. Commun.*, 1997, 1261.
- 8 F. Osterloh, W. Saak, D. Haase and S. Pohl, *Chem. Commun.*, 1996, 777.
- 9 G. J. Colpas, R. O. Day and M. J. Maroney, *Inorg. Chem.*, 1992, **31**, 5053.
- 10 D. K. Mills, Y. M. Hsiao, P. J. Farmer, E. V. Atnip, J. H. Reibenspies and M. Y. Darensbourg, *J. Am. Chem. Soc.*, 1991, **113**, 421.
- 11 D. J. Evans, S. Longhurst, R. L. Richards and J. R. Sanders, unpublished work.
- 12 G. M. Sheldrick, *Acta Crystallogr., Sect. A*, 1990, **46**, 467.
- 13 G. M. Sheldrick, SHELXL, Program for crystal structure refinement, University of Göttingen, Germany, 1993.

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