4166 *Inorg. Chem.* **1998,** *37,* 4166−4167

Protonation and Alkylation of a Dinuclear Nickel Thiolate Complex

Christian B. Allan,[†] Gerard Davidson, Suranjan B. Choudhury, Zhijie Gu, Kurethara Bose, Roberta O. Day, and Michael J. Maroney*

Department of Chemistry, University of Massachusetts, Amherst, Massachusetts 01003-4510

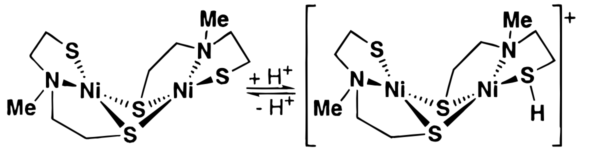
Received April 20, 1998

Protonation of transition metal ligand donor atoms is often invoked in metallobiochemical redox mechanisms. However, examples of complexes with thiol ligands are rare.[1−5] We report the synthesis and characterization of a novel protonated dithiolato-bridged dinickel(II) complex that features a terminal thiol ligand and the crystal structure of an analogous complex featuring an alkylated thiolate ligand. These dinuclear complexes may serve as models in exploring the chemistry of the cysteinate-bridged dimetallic active site of Ni,Fe hydrogenases (H_2ases).[6]

H_2ases catalyze the two-electron redox chemistry of H_2.[7] The most common form of the enzyme contains Ni, Fe, and S^{2-}. The 2.5 Å resolution crystal structure of the archetypical Ni,Fe H_2ase from *Desulfovibrio gigas* reveals that the active site is composed of nickel and iron centers bridged by a pair of cysteinate ligands. The remaining ligands to the nickel are terminal cysteinate ligands. Upon exposure to H_2, the oxidized forms are reduced first to an EPR-silent intermediate ($E_m \sim -150$ mV) and then further reduced to an EPR-active form (form C) ($E_m \sim -270$ mV) in one-electron steps that are coupled to the uptake of protons.[7,8] Form C is active enzyme, and has been shown to contain a solvent exchangeable proton from ENDOR studies.[9,10] One possibility is that form C represents an enzyme/product complex (i.e., a protonated Ni,Fe thiolate cluster).

Syntheses of the dimeric nickel thiolate complex $\{Ni[MeN(CH_2CH_2S)_2]\}$[11] (**1**) and the stable oxonium acid $[H(OEt_2)_2]^+\{B[3,5-(CF_3)_2C_6H_3]_4\}$[12] were carried out as previously described. Reaction of **1** with 1 equiv of $[H(OEt_2)_2]^+\{B[3,5-(CF_3)_2C_6H_3]_4\}^-$ leads to the formation of the monoprotonated complex, H(**1**)$^+$, which can be precipitated as its$\{B[3,5-(CF_3)_2C_6H_3]_4\}^-$ salt by addition of hexane in ~80% yield.[13] Salts with other anions (e.g., PF_6^- and ClO_4^-) may be prepared in similar yields by adding a slight excess of $Bu_4N(PF_6)$ or $Bu_4N(ClO_4)$ before the acid is added, whereupon they precipitate without addition of hexane.[13] The protonated complex is inactive in catalyzing H/D exchange in the presence of D_2 using an NMR assay.[14]

Scheme 1



A titration carried out on a CH_2Cl_2 solution of **1** by addition of solid samples of $[H(OEt_2)_2]^+\{B[3,5-(CF_3)_2C_6H_3]_4\}$ and monitoring the UV/vis spectrum reveals an isosbestic point at 327 nm. With the exception of two UV absorptions that are attributable to the $\{B[3,5-(CF_3)_2C_6H_3]_4\}^-$ anion (269, 278 nm), the spectral changes are reversed by the addition of a base (e.g., (i-Pr)$_2$(Et)N), and >90% of the starting dimer may be subsequently isolated from solution. These results are consistent with a reversible protonation leading to a single dimeric product (Scheme 1).

Analysis of nickel K-edge XAS data obtained from H(**1**)$^+$-$\{B[3,5-(CF_3)_2C_6H_3]_4\}^-$ demonstrates that the protonated product is still a dimer and that the structural perturbation that occurs upon protonation is small.[15] The "best fit" of the EXAFS obtained for **1** agrees very well with crystallographic results,[11] including a distinct feature that is attributable to a Ni−Ni vector at 2.683(2) Å (2.679(2) Å in the crystal structure). The protonated complex has an EXAFS spectrum very similar to that of the neutral dimer and includes a feature assigned to a Ni−Ni vector at 2.690(3) Å. Analysis of the EXAFS spectrum of H(**1**)$^+$ gives an average Ni−S bond distance (2.184(1) Å) that is 0.02 Å longer than in **1** (2.164(1) Å). If this change were localized on a single Ni−S bond, the change in the distance would be a maximum of 0.06 Å. This difference is too small to be resolved as a separate shell, but should increase the disorder in the average Ni−S distance as reflected in the value of σ^2 in the fit. The value of σ^2 shows a very modest increase from $1.2(2) \times 10^{-3}$ Å^2 to $2.2(1) \times 10^{-3}$ Å^2 upon protonation. Both of these values are small and indicate a small range of Ni−S distances in both complexes.

The XANES data obtained for **1** and for H(**1**)$^+\{B[3,5-(CF_3)_2C_6H_3]_4\}^-$ reveal features assigned to a 1s → 3d transition and to a 1s → 4p$_z$ transition that are typical of planar nickel

---

[†] Current address: Laboratory of Biochemistry, National Heart, Lung and Blood Institute, NIH, Bethesda, MD 20892.

(1) Sellmann, D.; Sutter, J. *ACS Symp. Ser.* **1996**, *653*, 101−116.
(2) Sellmann, D.; Becker, T.; Knoch, F. *Chem. Eur. J.* **1996**, *2*, 1092−1098.
(3) Sellmann, D.; Mahr, G.; Knoch, F.; Moll, M. *Inorg. Chim. Acta* **1994**, *224*, 45−59.
(4) Stephan, D. W. *Inorg. Chem.* **1984**, *23*, 2207−2210.
(5) Darensbourg, M. Y.; Longridge, E. M.; Payne, V.; Reibenspies, J.; Riordan, C. G.; Springs, J. J.; Calabrese, J. C. *Inorg. Chem.* **1990**, *29*, 2721−2726.
(6) Volbeda, A.; Garcin, E.; Piras, C.; de Lacey, A. L.; Fernandez, V. M.; Hatchikian, E. C.; Frey, M.; Fontecilla-Camps, J. C. *J. Am. Chem. Soc.* **1996**, *118*, 12989−12996.
(7) Albracht, S. P. J. *Biochim. Biophys. Acta* **1994**, *1188*, 167−204.
(8) Roberts, L. M.; Lindahl, P. A. *J. Am. Chem. Soc.* **1995**, *117*, 2565−2572.
(9) Fan, C.; Teixeira, M.; Moura, J.; Moura, I.; Huynh, B. H.; Le Gall, J.; Peck, H. D., Jr.; Hoffman, B. M. *J. Am. Chem. Soc.* **1991**, *113*, 20−24.
(10) Whitehead, J. P.; Gurbiel, R. J.; Bagyinka, C.; Hoffman, B. M.; Maroney, M. J. *J. Am. Chem. Soc.* **1993**, *115*, 5629−5635.
(11) Choudhury, S. B.; Pressler, M. A.; Mirza, S. A.; Day, R. O.; Maroney, M. J. *Inorg. Chem.* **1994**, *33*, 4831−4839.
(12) Brookhart, M.; Grant, B.; Volpe, A. F., Jr. *Organometallics* **1992**, *11*, 3920−3922.
(13) All solvents were carefully dried and distilled under N_2. Manipulations of solutions were carried out under N_2 by using standard Schlenk techniques. For H(**1**)$^+\{B[3, 5-(CF_3)_2C_6H_3]_4\}^-$: $[H(OEt_2)_2]^+\{B[3, 5-(CF_3)_2C_6H_3]_4\}^-$ (144 mg, 0.144 mmol) was added as a solid to a solution of **1** (60.0 mg, 0.144 mmol) in CH_2Cl_2 (2 mL). Hexane (1 mL) was added prior to cooling to −20 °C. The resulting precipitate was collected by filtration, washed with Et_2O, and dried in vacuo. Yield = 135 mg, 74%. Anal. Calcd for $BC_{42}H_{35}N_2S_4F_{24}Ni_2$: C, 39.43; H, 2.75; N, 2.20. Found: C, 37.80; H, 2.69; N, 2.23. For H(**1**)$^+(PF_6)^-$: The product precipitated immediately, and was collected by filtration, washed with Et_2O, and dried in vacuo. Yield = 65.0 mg, 80%. Anal. Calcd for $C_{10}H_{23}N_2S_4Ni_2PF_6$: C, 21.38; H, 4.12; N, 4.98. Found: C, 20.87; H, 3.93; N, 4.71.
(14) Albeniz, A. C.; Heinekey, D. M.; Crabtree, R. H. *Inorg. Chem.* **1991**, *30*, 3632−3635.
(15) Transmission XAS data were obtained at ~30 K on beam line X9B at the National Synchrotron Light Source. Fourier-filtered EXAFS data were analyzed with FT limits of $k = 2-13$ Å^{-1} and backtransform limits of $r = 1.1-2.6$ Å (uncorrected for phase shifts), as described previously (see ref 18). Analysis results are given in the Supporting Information.

S0020-1669(98)00446-7 CCC: $15.00

coordination.[16] The nickel K-edge energy shifts from 8339.0(2) eV to 8339.8(2) eV upon protonation. This increase is consistent with a slight decrease in the average electron density at the nickel centers upon protonation. The magnitude of the edge shift (0.8 eV) is comparable to that observed for the edge energy shifts that occur between the oxidized forms of H_2ase and form C.[17,18]

NMR spectra obtained from H(**1**)$^+$ help to further characterize the site of protonation and the nuclearity of the product. The 75 MHz ^{13}C NMR spectrum of **1** in CD_2Cl_2 consists of five lines (71.8, 69.9, 44.8, 29.9, 27.0 ppm relative to internal TMS) that arise from four methylene groups and the N−Me group. Monoprotonation would be expected to break the symmetry, leading to the observation of 10 ^{13}C NMR resonances in addition to those associated with the anion. Nine of the expected resonances have been observed (15.7, 35.4, 66.7, 119.0, 120.6, 124.2, 127.8, 131.4, 136.2 ppm in CD_3NO_2). The protonated product has also been examined by ^{2}H NMR for the presence of a thiol. The ^{2}H NMR spectrum of ^{2}H(**1**)$^+$$\{B[3,5\text{-}(CF_3)_2C_6H_3]_4\}^-$ in CD_3NO_2 reveals a single peak at 1.93 ppm, a chemical shift consistent with other RSH and M−SH ^{1}H NMR resonances (e.g., MeSH, 1.78 ppm; $Fe(CO)_4(MeSH)$, 2.4 ppm).[19]

The structure of H(**1**)$^+$ described above is supported by the crystal structure of an analogous complex that features an alkylated thiolate ligand. Reaction of **1** with 1 equiv of benzyl chloride gives a crude sample of {[(*μ*-2-mercaptoethyl)(2-mercaptoethyl)-methylaminato(2−)][(*μ*-2-mercaptoethyl)(2-benzylthioethyl)methyl-aminato(1−)]dinickel(II)}Cl, (**2**)Cl, upon removal of the solvent. The product is soluble in methanol, from which (**2**)PF_6 is obtained in 89% overall yield upon addition of a solution of $NH_4(PF_6)$ in ethanol. Crystals of (**2**)PF_6 suitable for diffraction studies were obtained from a methanol solution by vapor-phase diffusion of Et_2O at −20 °C.[20] The structure of **2** is very similar to **1**, except that a single terminal thiolate has been alkylated (Figure 1).[11] The $[NiNS_3]_2$ core structure is little perturbed by alkylation and features a Ni−S distance involving the thioether S-donor atom that is 0.02 Å longer than the Ni−S bond involving the terminal thiolate S donor. These distances are similar to the average of the two chemically equivalent terminal Ni−S bonds in **1** (2.154-(4) Å). The change in the Ni−S distance observed upon alkylation is in agreement with observations in mononuclear nickel systems.[21] The Ni−Ni distance is also little affected by alkylation of a terminal thiolate (2.679(2) Å in **1** vs 2.640(1) Å in **2**).

The effects on the redox chemistry of the dinuclear complexes due to protonation or alkylation show trends similar to those of mononuclear Ni[21] and Fe[2] systems. Cyclic voltammetric studies of **1** in CH_2Cl_2/0.05 M $[(n\text{-}Bu)_4N]\{B[3,5\text{-}(CF_3)_2C_6H_3]_4\}$ solution show an irreversible, one-electron oxidation with $E_{p_a} = +390$ mV with no reductions observed out to the cathodic solvent limit (−925 mV). This is in agreement with the reported electrochemistry of this complex ($E_{p_a} = +490$ mV, no cathodic processes > −1 V vs NHE in CH_2Cl_2/0.1 M $NBu_4(ClO_4)$ solution[11]). Alkylation of the dimer shifts the oxidation potential anodically (E_{p_a} = 1.2 V vs NHE) and causes the appearance of an irreversible reduction with $E_{p_c} = -800$ mV. Protonation of **1** leads to a shift of E_{p_c} to +960 mV and the observation of a cathodic process at $E_{p_c} = -550$ mV.[22] Although these changes likely arise to a large extent from the change in charge on the complex, it is noteworthy that the potential difference between the oxidized and reduced species is smaller for protonation (1.5 V) than for alkylation (2.0 V).

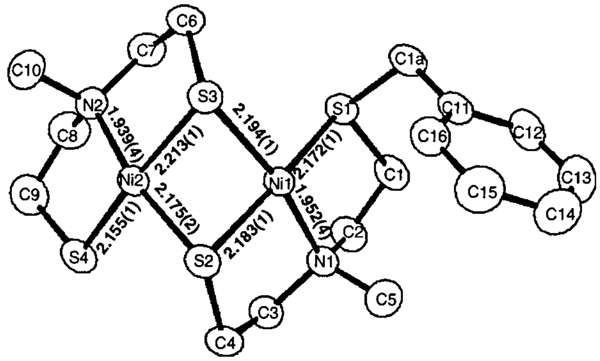


Figure 1. ORTEP plot of **2** with thermal ellipsoids at the 30% probability level and the H atoms omitted for clarity. Distances shown are in angstroms. The Ni atoms are in a disorted planar coordination environment with trans angles: S1−Ni1−S2 = 176.03(5)°, N1−Ni1−S3 = 169.09-(12)°, S3−Ni2−S4 = 174.35(5)°, N2−Ni2−S2 = 169.64(12)°.

Studies of the nickel site in H_2ases employing XAS have shown that the structure is insensitive to the redox state of the enzyme, and that the change in the Ni K-edge energy observed during redox cycling of the enzyme is too small to involve both Ni(III) and Ni(I) species.[17,18] The studies presented above show that varying the state of protonation of the terminal thiolate ligands in a model system with a core structure that resembles the H_2ase active site leads to changes in the redox potentials over a wide range without inducing large changes in the structure of the complex.

Acknowledgment. This work was supported by a grant from the NIH (GM38829, M.J.M.). The National Synchrotron Light Source, Brookhaven National Lab, is supported by the U.S. Department of Energy, Division of Materials Sciences and Division of Chemical Sciences. Beam line X9B at NSLS is supported by NIH Grant RR-01633.

Supporting Information Available: Figure illustrating spectral changes accompanying the titration of **1** and EXAFS spectra and fits for **1** and H(**1**)$^+$ and tables of EXAFS analysis for **1** and H(**1**)$^+$ and additional details of the crystallographic studies of **2**, including atomic coordinates, bond lengths and angles, and hydrogen atom parameters (11 pages). Ordering information is given on any current masthead page.

IC9804465

---

(16) Colpas, G. J.; Maroney, M. J.; Bagyinka, C.; Kumar, M.; Willis, W. S.; Suib, S. L.; Mascharak, P. K.; Baidya, N. *Inorg. Chem.* **1991**, *30*, 920−928.

(17) Gu, Z.; Dong, J.; Allan, C. B.; Choudhury, S. B.; Franco, R.; Moura, J. J. G.; Moura, I.; LeGall, J.; Przybyla, A. E.; Roseboom, W.; Albracht, S. P. J.; Axley, M. J.; Scott, R. A.; Maroney, M. J. *J. Am. Chem. Soc.* **1996**, *118*, 11155−11165.

(18) Bagyinka, C.; Whitehead, J. P.; Maroney, M. J. *J. Am. Chem. Soc.* **1993**, *115*, 3576−3585.

(19) Darensbourg, M. Y.; Liaw, W.-F.; Riordan, C. G. *J. Am. Chem. Soc.* **1989**, *111*, 8051−8052.

(20) $PhCH_2Cl$ (117 mL, 1.03 mmol) was dissolved in CH_2Cl_2 (2 mL) and added dropwise to a stirring solution of **1** (426 mg, 1.03 mmol) in CH_2Cl_2 (10 mL). After 4 h at room temperature, the mixture was heated to reflux for 2 h. Upon cooling, the solvent was removed and the solid was redissolved in methanol (10 mL). This solution was filtered, and a solution of $NH_4(PF_6)$ (670 mg, 4.11 mmol) in ethanol (10 mL) was added dropwise. The product, **2**(PF_6), precipitated and was collected by filtration, washed with Et_2O, and dried in vacuo. Yield = 595 mg (89%). Anal. Calcd for $C_{17}H_{29}N_2S_4Ni_2PF_6$: C, 31.31; H, 4.48; N, 4.30. Found: C, 31.06; H, 4.51; N, 4.30. The crystals obtained from MeOH/Et_2O form in space group $P\bar{1}$ (No. 2), a = 9.688(2) Å, b = 11.612(2) Å, c = 13.201-(3) Å, α = 64.53(2)°, β = 87.91(2)°, γ = 71.48(2)°, V = 1262.6(4) Å^3, and Z = 2. Full-matrix least-squares refinement on F^2 employed all of the data and led to a final R = 4.0% for 3220 observed reflections.

(21) Farmer, P. J.; Reibenspies, J. H.; Lindahl, P. A.; Darensbourg, M. Y. *J. Am. Chem. Soc.* **1993**, *115*, 4665−4674.

(22) Cyclic voltammetric measurements were conducted by using a BAS CV 50W voltammetric analyzer on solutions of complexes prepared in 0.05 M $n\text{-}Bu_4N\{B[3,5\text{-}(CF_3)_2C_6H_3]_4\}/CH_2Cl_2$ solution. The standard three-electrode cell consisted of a glassy carbon working electrode, a Ag wire pseudo reference electrode, and a Pt auxiliary electrode. Potentials were calibrated to the ferrocene/ferrocenium couple and converted to the NHE reference by setting the potential of this couple to +400 mV vs NHE. The values reported were obtained using a 250 mV/s sweep rate.