Nickel(II) Complexes with the [NiN$_x$Se$_y$] Chromophore in Different Coordination Geometries: Search for a Model of the Active Site of [FeNiSe] Hydrogenases

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Recent studies have revealed the presence of a unique Ni–Se interaction in hydrogenases (H$_2$ase) from several microorganisms.[1–5] X-ray absorption spectroscopic (XAS) studies on H$_2$ase from *Desulfovibrio baculatus* indicate that the active site of this enzyme contains nickel with 3–4 N/O atoms at 2.06 Å, 1–2 S/Cl atoms at 2.17 Å, and 1 Se atom at 2.44 Å in its first coordination sphere.[3] The geometry of the nickel center has been interpreted as either pseudooctahedral or distorted trigonal bipyramidal. The possibility of having more than one selenium from selonocysteine coordinated to the nickel center at the active site of the H$_2$ase isolated from *Methanococcus vannielii* has also been proposed.[6] Though close similarities in XAS parameters of H$_2$ase from *D. baculatus* (a selenium-containing H$_2$ase, [FeNiSe] H$_2$ase)[3] and *Thiocapsa roseopersicina* (H$_2$ase with no selenium, [FeNi] H$_2$ase)[7] suggest that these two enzymes are structurally similar, the two enzymes exhibit distinctly different reactivities. For example, *T. roseopersicina* H$_2$ase can be oxidized to states which are EPR active[8] whereas *D. baculatus* H$_2$ase does not generate any significant EPR-active species upon oxidation. Catalytic properties of these two enzymes are also different.[9]

Elucidation of the structure of the nickel site in the [FeNiSe] H$_2$ase as well as the structural basis for the functional differences between the Se- and non-Se-containing H$_2$ase clearly await systematic exploration of the structural, spectroscopic, and reactivity parameters of nickel complexes with Se-, N-, and O-donor ligands. Along this line we report here the structures and properties of [Ni(terpy)(2,4,6-(Me)$_3$C$_6$H$_2$Se)$_2$] (1), [Ni(terpy)(PhSe)$_2$]$_2$ (2), [Ni(dmp)(2,4,6-(Me)$_3$C$_6$H$_2$Se)$_2$] (3), and [Ni(dmp)(PhSe)$_2$]$_2$·2CH$_3$CN (4), which are the first few examples of nickel(II) complexes with Se and N donor ligands.[10] The reaction of Ni(terpy)Cl$_2$[11] in a CH$_3$CN/EtOH mixture with 2 equiv of (2,4,6-(Me)$_3$C$_6$H$_2$Se$^-$)Na$^+$ affords [Ni(terpy)(2,4,6-

(Me)$_3$C$_6$H$_2$Se)$_2$] (1),[12] while, with Me$_4$N$^+$PhSe$^-$, the dimeric complex [Ni(terpy)(PhSe)$_2$]$_2$ (2) is obtained in high yield. When the terpy ligand is substituted with dmp, the monomeric tetrahedral complex [Ni(dmp)(2,4,6-(Me)$_3$C$_6$H$_2$Se)$_2$] (3)[13] and the dimeric pentacoordinated complex [Ni(dmp)(PhSe)$_2$]$_2$·2CH$_3$-CN (4)[14] are obtained. The structures of 1, 3, and 4 are shown in Figures 1–3. Compound 2 has been characterized by ^{1}H NMR (Table I) and electronic absorption spectroscopy.[15]

Steric repulsion between the bulky selenolate ligands gives rise to a distorted trigonal bipyramidal (tbp) geometry around the nickel center in 1 (Figure 1). The two Se atoms and the central N atom of the terpy ligand lie in the equatorial plane, while the other two N atoms of terpy occupy the axial positions. Similar nickel(II) complexes with bulky thiolate ligands (RS$^-$, R = 2,4,6-(*i*-Pr)$_3$C$_6$H$_2$ and 2,6-(Me)$_2$C$_6$H$_3$) have been previously reported by this group.[16] A distorted tetrahedral geometry is noted in complex 3 in which the bidentate ligand dmp replaces terpy as the N-donor ligand (Figure 2). With the simple selenolate PhSe$^-$, the centrosymmetric dimeric complex 4 is isolated. The coordination geometry around each nickel in 4 is distorted tbp with two N and one Se (bridging) atoms in the equatorial plane, while the axial positions are occupied by one terminal and one bridging Se donor atoms (Figure 3).

The Ni–Se bond distances in these mixed-ligand complexes vary only to a small extent. The average Ni–Se distances of 2.440 (3) and 2.436 (1) Å for 1 and 4, respectively, are very close to the Ni–Se distance reported for the *D. baculatus* H$_2$ase (EXAFS measurements).[3] The Ni–Se distance in the tetrahedral complex 3 is, however, shorter (2.364 (1) Å) than that in the biological [NiSe] site. It is also interesting to note that the average Ni–Se distances in homoleptic nickel(II) complexes of Se-donor

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(10) Terpy = 2,2′,2″-tripyridine; dmp = 2,9-dimethyl-1,10-phenanthroline; PhSe = benzeneselenolate; (2,4,6-(Me)$_3$C$_6$H$_2$Se) = 2,4,6-trimethylbenzeneselenolate.
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(12) X-ray analysis (for all X-ray data, Siemens P4/RA machine, Cu Kα (1.541 78 Å) radiation, Nickel filter, 125 K): dark plates from acetonitrile; NiC$_{33}$H$_{33}$N$_3$Se$_2$ (1), monoclinic space group $P2_1/n$, a = 13.170 (6) Å, b = 16.091 (5) Å, c = 15.111 (8) Å, β = 114.42 (2)°, V = 2916 (2) Å^3, Z = 4, d_{calcd} = 1.57 (1) g/cm^3, 2730 reflections used ($F > 4.0\sigma$-(F)), R = 0.048, R_w = 0.050. The structure was solved by direct methods (SHELXTL PLUS, version 4.2, 1990). One of the Se atoms of 1 is disordered. Initially, the two atoms of the disordered pair were refined with variable occupancy. Since the refined occupancies were 0.506/0.494, they were fixed at 0.50 for both atoms in subsequent cycles of refinements. The disordered Se(1) atoms were refined isotropically, and the average position is shown in Figure 1.
(13) X-ray analysis: dark needles from acetonitrile; NiC$_{32}$H$_{34}$N$_2$Se$_2$ (3), triclinic space group $P\bar{1}$, a = 8.160 (3) Å, b = 10.622 (4) Å, c = 16.757 (7) Å, α = 98.33 (3)°, β = 94.44 (3)°, γ = 96.45 (3)°, V = 1421.5 (9) Å^3, Z = 2, d_{calcd} = 1.55 (1) g/cm^3, 2063 reflections used ($F > 6.0\sigma(F)$), R = 0.097, R_w = 0.103 (minor decomposition during data collection). The structure was solved by direct methods.
(14) X-ray analysis: dark blocks from acetonitrile; Ni$_2$C$_{56}$H$_{50}$N$_6$Se$_4$ (4), monoclinic space group $P2_1/c$, a = 12.108 (4) Å, b = 9.410 (1) Å, c = 22.347 (3) Å, β = 97.60 (1)°, V = 2523.8 (1) Å^3, Z = 2, d_{calcd} = 1.63 (1) g/cm^3, 2841 reflections used ($F > 4.0\sigma(F)$), R = 0.036, R_w = 0.045. The structure was solved by direct methods.
(15) Electronic spectroscopic data (DMSO; λ, nm (ε, M^{-1} cm^{-1})): **1**, 1025 (60), 534 (2900), 320 (sh, 20 500), 305 (20 000), 283 (22 300); **2**, 1010 (110), 485 (4100), 410 (5000), 320 (55 000), 315 (sh, 54 500), 283 (49 000), 275 (48 500); **3**, 900 (210), 565 (2500), 490 (2300), 300 (26 000), 275 (34 500); **4**, 883 (390), 590 (5000), 508 (6300), 450 (6200), 315 (sh, 26 000), 300 (sh, 37 500), 275 (69 000).
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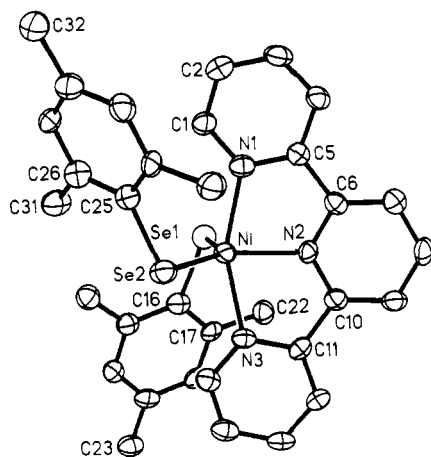
Figure 1. Thermal ellipsoid plot (50% probability level) of **1**. Hydrogen atoms are omitted for clarity. Selected bond distances in Å: Ni–Se(1) = 2.466 (3), Ni–Se(2) = 2.387 (2), Ni–N(1) = 2.109 (5), Ni–N(2) = 1.976 (6), Ni–N(3) = 2.106 (5), Se(2)–C(25) = 1.930 (7), C(26)–C(31) = 1.505 (10), C(5)–C(6) = 1.469 (10). Selected bond angles in deg: Se(1)–Ni–Se(2) = 129.2 (1), N(1)–Ni–N(2) = 78.4 (2), N(2)–Ni–N(3) = 78.4 (2), N(1)–Ni–N(3) = 156.7 (3), Ni–Se(2)–C(25) = 109.2 (3), Se(2)–Ni–N(1) = 97.8 (2), Se(2)–Ni–N(2) = 121.9 (2).
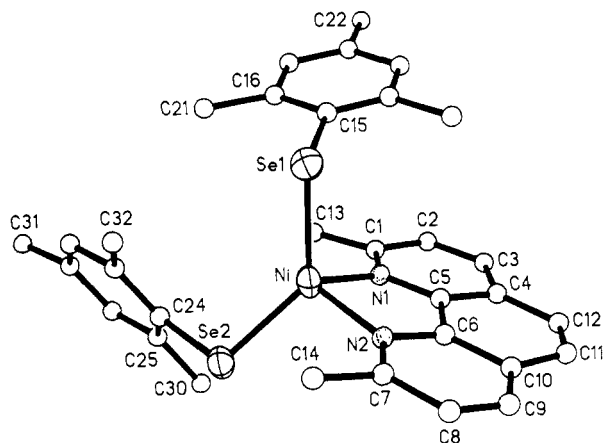

Figure 2. Computer-generated drawing of **3**. Lighter atoms have been refined isotropically. Hydrogen atoms are not shown. Selected bond distances in Å: Ni–Se(1) = 2.384 (3), Ni–Se(2) = 2.340 (3), Ni–N(1) = 2.010 (16), Ni–N(2) = 2.009 (14), Se(1)–C(15) = 1.927 (17), C(16)–C(21) = 1.501 (28), C(1)–C(13) = 1.466 (30), C(5)–C(6) = 1.454 (29). Selected bond angles in deg: Se(1)–Ni–Se(2) = 129.6 (1), Se(1)–Ni–N(1) = 101.4 (4), Se(1)–Ni–N(2) = 108.5 (4), N(1)–Ni–N(2) = 82.8 (6), Ni–Se(1)–C(15) = 105.9 (5), Ni–Se(2)–C(24) = 103.6 (4).

ligands are always shorter (2.255 (2)–2.305 (2) Å)[17] than that reported for the enzyme. The Ni–N distances in **1**, **3**, and **4** are close to the values reported for analogous complexes.[18] Significant deviations from ideal bond angles are observed in these complexes due to steric reasons.

The nickel selenolate complexes reported in this account are extremely sensitive to oxygen, more so than the corresponding sulfur analogues. Reduction of **1** with dithionite in DMF solution gives rise to a Ni(I) species ($g_\parallel$ = 2.249, $g_\perp$ = 2.103), the CO adduct of which exhibits a rhombic EPR signal (g = 2.204, 2.131, 2.024) with hyperfine coupling splitting at the g_3 region (12 G)

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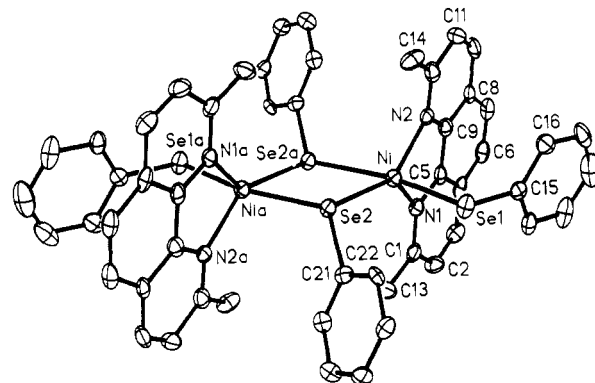

Figure 3. Thermal ellipsoid plot (50% probability level) of **4**. Hydrogen atoms and the solvent molecules of crystallization have been omitted for clarity. Selected bond distances in Å: Ni–Se(1) = 2.440 (1), Ni–Se(2) = 2.432 (1), Ni–N(1) = 2.025 (3), Ni–N(2) = 2.032 (4), Ni–Se(2a) = 2.605 (1), Se(1)–C(15) = 1.914 (5), C(1)–C(13) = 1.488 (7). Selected bond angles in deg: Se(1)–Ni–Se(2) = 93.2 (1), Se(1)–Ni–N(1) – 97.4 (1), Se(2)–Ni–N(1) = 130.8, Se(1)–Ni–N(2) = 96.4 (1), N(1)–Ni–N(2) = 82.1 (1), Se(2)–Ni–Se(2a) = 73.3 (1), Se(2)–Ni–N(2) = 144.1 (1).

Table I. ^{1}H NMR Data (Solvent $(CD_3)_2SO$, 300 MHz, 298 K, δ (ppm) from TMS)

complex	resonances of the terpy/dmp ligand	resonances of the selenolate ligand
1	165.80 (2 H), 78.28 (2 H), 74.72 (2 H), 49.62 (2 H), 23.01 (1 H), 17.46 (2 H)	27.44 (6 H, p-CH$_3$), 18.40 (4 H, m), 17.16 (12 H, o-CH$_3$)
2	149.17 (2 H), 74.92 (2 H), 72.80 (2 H), 48.07 (2 H), 14.99 (1 H), 12.91 (2 H)	13.86 (4 H, m), –14.19 (6 H, o,p)
3	72.23 (2 H), 24.29 (2 H), 21.48 (2 H), –2.42 (6 H)	28.64 (6 H, p-CH$_3$), 23.16 (12 H, o-CH$_3$), 21.62 (4 H, m)
4	67.01 (2 H), 22.53 (2 H), 15.79 (2 H), 1.77 (6 H)	16.83 (4 H, m), –15.38 (4 H, o), –18.60 (2 H, p)

(supplementary material).[19] Reaction of NaBH$_4$ with **1** at low temperature (~250 K) does not afford any EPR-detectable hydride adduct. This is quite in contrast to the sulfur analogue of **1**,[16] which readily affords the corresponding hydride adduct under similar conditions. Decreased stability of the hydride intermediate due to the presence of Se at the active site has been proposed for *D. baculatus* H$_2$ase.[4,9] The observed reactivities of the model complexes (**1** and its S-analogues) support this conclusion.

In summary, the structures, properties, and reactivities of the first series of nickel(II) complexes with $[NiN_xSe_y]$ chromophores have been reported. Comparison of these data with those for the sulfur analogues is expected to provide insight into the role of selenium in the Se-containing H$_2$ase. The X-ray absorption spectroscopic (XAS) data for these complexes (experiments presently in progress) will be quite useful in the analysis of XAS data obtained with the enzyme(s).

Supplementary Material Available: ^{1}H NMR spectra of **1–4**, EPR spectra of the reduced species from **1** and its CO adduct, and tables of positional parameters, anisotropic thermal parameters, and bond distances and angles for **1**, **3**, and **4** (19 pages). Ordering information is given on any current masthead page.

(19) On reduction with dithionite, the tetrahedral complex **3** gives rise to a nickel(I) species that exhibits an axial EPR signal with g = 2.415 and 2.138. Substrate binding studies with all of these complexes are in progress at the present time.