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Rhenium(V) Oxo Complexes of Novel N_2S_2 Dithiourea (DTU) Chelate Ligands: Synthesis and Structural Characterization

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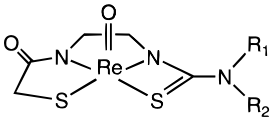
The compounds RNHC(=S)NH(CH$_2$)$_n$NHC(=S)NHR were prepared in a search for new, relatively small N_2S_2 ligands. These dithiourea (DTU) ligands are the first chelates containing two potentially bidentate thiourea moieties. A one-step reaction of 1,3-diaminopropane (**1**) with aryl or alkyl isothiocyanates or of 1,2-diaminoethane (**2**) with phenyl isothiocyanate afforded the target ligands in excellent yields (95−98%). The $\text{Re}^{V}{=}\text{O}$ complexes of RNHC(=S)NH(CH$_2$)$_3$NHC(=S)NHR ligands were obtained through ligand exchange reactions with Re(V) precursors. The chemistry required neither protection of the sulfur atoms for ligand synthesis nor deprotection prior to metal complexation. The structure of (1-phenyl-3-(3-phenylthioureido)propyl]thioureato)oxorhenium(V) (**7a**), determined by X-ray diffraction methods, revealed the expected pseudo-square-pyramidal geometry with an N_2S_2 basal and an apical oxo donor set. Both coordinated N's (N_c) were deprotonated. One uncoordinated N (N_u) was deprotonated, producing a neutral complex containing an unexpected new type of dianionic, four-membered N,S chelate. In the crystal, the N_u atoms, N(3)H and N(4), of one complex each formed an H-bond with N(4) and N(3)H, respectively, of a symmetry-related complex. The N_c−C−S bond angles (106.1(6) and 101.5(6)°) were severely distorted from the 120° expected for an sp^2-hybridized C. However, these small bite angles and the large N−Re−N bond angle (86.1(3)°) allowed for the formation of two four-membered chelate rings with normal Re−N and Re−S bond distances. Attempts to prepare complexes with the PhNHC(=S)NH(CH$_2$)$_2$NHC(=S)NHPh ligand were unsuccessful. These results suggest that a central five-membered chelate ring is too small to accommodate bidentate coordination of both thiourea moieties. NMR studies in methanol established that the neutral complex with one uncoordinated N deprotonated was the favored form in neutral and basic solutions. However, under acidic conditions, a cationic form with both uncoordinated N's protonated was favored.

Introduction

We have been exploring the utility of thiourea moieties in the construction of novel N_2S_2 ligands. N_2S_2 ligands have important radiopharmaceutical applications[1] and are widely used to model the structure, function, and spectroscopic behavior of metalloproteins.[2−5] Thiourea and its derivatives, which have long attracted attention as ligands, usually coordinate through the sp^2-hybridized sulfur in a monodentate manner.[6−11] However, a few examples of bidentate coordination through sulfur and one deprotonated nitrogen atom have been reported.[12−17] We recently described[12] the synthesis and characterization of a new class of quadridentate N_2S_2 chelating agents based on thiol, amide, and thiourea donor groups. The thiol−amide−thiourea (TATU) ligands formed small neutral $\text{Re}^{V}{=}\text{O}$ complexes with bidentate N,S coordination of the thiourea moiety (I). However, the thiol required protection prior to ligand synthesis and deprotection prior to metal complexation.



I

Since incorporation of a potentially bidentate thiourea moiety into a multidentate ligand system was successful with the TATU system, we were encouraged to study the reaction of diamines with several isothiocyanates leading to formation of novel, symmetrical dithiourea N_2S_2 (DTU) ligands in one step. Ligand synthesis was followed by direct preparation as well as spectroscopic and structural characterization of $\text{Re}^{V}{=}\text{O}$(DTU) type complexes.

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(1) Baldas, J. *Advances in Inorganic Chemistry*; Academic Press, Inc.: San Diego, CA, 1994; Vol. 41, p 1.

(2) Maroney, M. *Comments Inorg. Chem.* **1995**, *17*, 347.

(3) Frydendahl, H.; Toftlund, H.; Becher, J.; Dutton, J. C.; Murray, K. S.; Taylor, L. F.; Anderson, O. P.; Tiekink, R. T. *Inorg. Chem.* **1995**, *34*, 4467.

(4) Peng, G.; Nichols, J.; McCullough, E. A., Jr.; Spence, J. T. *Inorg. Chem.* **1994**, *33*, 2857.

(5) Sellman, D.; Ruf, R.; Knoch, F.; Moll, M. *Inorg. Chem.* **1995**, *34*, 4745.

(6) Vorob'ev-Desyatovskii, N. V.; Kukushkin, Y. N.; Sibirskaya, V. V. *Koord. Khim.* **1985**, *11*, 1299.

(7) Lis, T. *Acta Crystallogr.* **1976**, *B32*, 2707.

(8) Lis, T. *Acta Crystallogr.* **1977**, *B33*, 944.

(9) Lis, T.; Starynowicz, P. *Acta Crystallogr.* **1985**, *C41*, 1299.

(10) Rochon, F. D.; Melanson, R.; Kong, P. C. *Acta Crystallogr.* **1990**, *C46*, 571.

(11) Abrams, M. J.; Davison, A.; Faggiani, R.; Jones, A. G.; Lock, C. J. L. *Inorg. Chem.* **1984**, *23*, 3284.

(12) Lipowska, M.; Hansen, L.; Taylor, A., Jr.; Marzilli, L. G. *Inorg. Chem.*, in press.

(13) Bodensieck, U.; Carraux, Y.; Stoeckli-Evans, H.; Suss-Fink, G. *Inorg. Chim. Acta* **1992**, *195*, 135.

(14) Watson, P. L.; Albanese, J. A.; Calabrese, J. C.; Ovenall, D. W.; Smith, R. G. *Inorg. Chem.* **1991**, *30*, 4638.

(15) Piraino, P.; Bruno, G.; Tresoldi, G.; Faraone, G.; Bombieri, G. *J. Chem. Soc., Dalton Trans.* **1983**, 2391.

(16) Bosman, W. P.; Gal, A. W. *Cryst. Struct. Commun.* **1976**, *5*, 703.

(17) Janakiram-Sayala, C.; Bosman, W. P.; Willemse, J.; Cras, J. A. *Recl. Trav. Chim. Pays-Bas* **1980**, *99*, 314.

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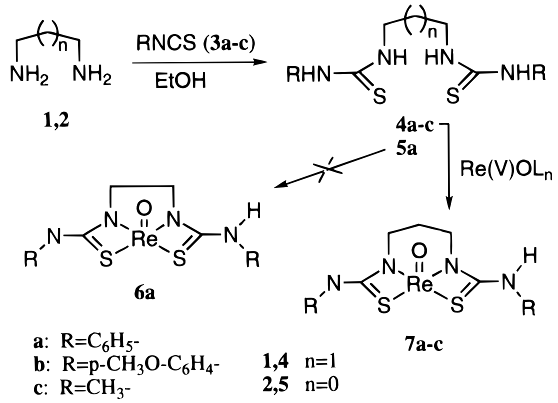
Scheme 1



Experimental Section

1,3-Diaminopropane (**1**), 1,2-diaminoethane (**2**), and all isothiocyanates (**3**) were obtained from Aldrich. ReOCl$_3$(Me$_2$S)(OPPh$_3$)[18,19] and ReO$_2$I(PPh$_3$)$_2$[20] were prepared as described previously. All solvents were of reagent grade and were used as received. Air-sensitive reactions were carried out under a nitrogen atmosphere. Column chromatography was conducted on Merck silica gel 60 (230−400 mesh ASTM). Thin-layer chromatography (TLC) was carried out on Merck silica gel 60 F 254 plates developed in chloroform (CHCl$_3$)/methanol (MeOH) mixtures and visualized by UV illumination at 254 nm and/or iodine reagent. Elemental analyses were performed by Atlantic Microlabs, Atlanta, GA. NMR spectra were recorded on a General Electric QE-300 spectrometer with tetramethylsilane (TMS) as an internal standard. Melting points are uncorrected.

Preparation of Ligands (Scheme 1). General Procedures for Compounds 4a−c and 5a. To a solution of diamine (**1** or **2**) (2.5 mmol) in ethanol (20 mL), was slowly added the appropriate isothiocyanate **3** (5 mmol) at room temperature under a nitrogen atmosphere. The reaction mixture was stirred at room temperature until TLC monitoring indicated complete conversion of the diamine. The mixture was then concentrated *in vacuo*, and the resulting residue was purified by column chromatography on silica gel (CHCl$_3$/EtOH, up to 20% EtOH) and crystallized from ethanol. The reported yields correspond to analytically pure products.

1-Phenyl-3-[3-(3-phenylthioureido)propyl]thiourea (4a). This compound was obtained from **1** and **3a** in 98% yield: mp 135 °C; ^{1}H NMR (DMSO-d_6) δ 1.79 (quin, J = 6.6 Hz, 2H), 3.52 (q, J = 6.6 Hz, 4H), 7.11 (t, J = 7.2 Hz, 2H), 7.29−7.40 (m, 8H), 7.80 (s, 2H), 9.54 (s, 2H). Anal. Calcd for $C_{17}H_{20}N_4S_2$: C, 59.27; H, 5.85; N, 16.27. Found: C, 59.17; H, 5.89; N, 16.14.

1-(4-Methoxyphenyl)-3-[3-(3-(4-methoxyphenyl)thioureido)-propyl]thiourea (4b). This compound was obtained from **1** and **3b** in 96% yield: mp 155 °C; ^{1}H NMR (DMSO-d_6) δ 1.73 (quin, J = 6.3 Hz, 2H), 3.46 (q, J = 6.3 Hz, 4H), 3.73 (s, 6H), 6.89 (d, J = 8.7 Hz, 4H), 7.19 (d, J = 8.7 Hz, 4H), 7.55 (s, 2H), 9.31 (s, 2H). Anal. Calcd for $C_{16}H_{24}N_4O_2S_2$: C, 56.41; H, 5.98; N, 13.85. Found: C, 56.28; H, 6.08; N, 13.75.

1-Methyl-3-[3-(3-methylthioureido)propyl]thiourea (4c). This compound was obtained as an oil from **1** and **3c** in 95% yield: ^{1}H NMR (CDCl$_3$) δ 1.85 (quin, J = 6.8 Hz, 2H), 2.98 (s, 6H), 3.74 (q, J = 6.8 Hz, 4H), 6.21 (b s, 2H), 6.74 (b s, 2H). Anal. Calcd for $C_7H_{16}N_4S_2{\cdot}C_2H_5OH$: C, 38.84; H, 7.61; N, 24.16. Found: C, 38.69; H, 7.55; N, 23.92.

1-Phenyl-3-[2-(3-phenylthioureido)ethyl]thiourea (5a). This compound was obtained from **2** and **3a** in 98% yield: mp 193 °C; ^{1}H NMR (DMSO-d_6) 3.65 (s, 4H), 7.08 (t, J = 6.9 Hz, 2H), 7.25−7.35 (m, 8H), 7.79 (s, 2H), 9.55 (s, 2H). Anal. Calcd for $C_{16}H_{18}N_4S_2$: C, 58.15; H, 5.49; N, 16.96. Found: C, 58.06; H, 5.52; N, 16.91.

Preparation of Complexes. General Procedure for Compounds 7a,b. To a stirred solution of ligands **4a,b** (1 mmol) in methanol (20 mL) was added 1 N NaOAc in methanol (10 mL, 10 mmol) followed by solid ReOCl$_3$(Me$_2$S)(OPPh$_3$) (1 mmol). The reaction mixture was heated at reflux for 2 h, at which time the green color of the starting metal compound had been replaced by a brownish-orange color. After being cooled to room temperature, the reaction mixture, diluted with ethyl acetate (50 mL), was washed with water. The organic layer was separated from the mixture, dried over MgSO$_4$, and concentrated *in vacuo*. Purification by column chromatography (silica gel, CHCl$_3$/MeOH, up to 15% MeOH) was followed by crystallization from ethanol to give **7a,b** as analytically pure samples.

[1-Phenyl-3-[3-(3-phenylthioureido)propyl]thioureato]oxorhenium(V) (7a): yield 53%; FT IR (cm^{-1}) 2918, 2847 (C−H), 1602, 1573 (C−N), 984 (Re═O); ^{1}H NMR (DMSO-d_6) δ 1.94−2.07 (m, 1H), 2.31−2.36 (m, 1H), 3.23−3.31 (m, 2H), 3.77−3.81 (m, 2H), 7.24 (d, J = 7.8 Hz, 6H), 7.40 (t, J = 7.8 Hz, 4H); ^{13}C NMR (DMSO-d_6) δ 195.1, 140.8, 129.5, 125.8, 124.3, 48.1, 30.8. Anal. Calcd for $C_{17}H_{17}N_4OReS_2$: C, 37.55; H, 3.16; N, 10.30. Found: C, 37.59; H, 3.23; N, 10.19.

[1-(4-Methoxyphenyl)-3-[3-(3-(4-methoxyphenyl)thioureido)-propyl]thioureato]oxorhenium(V) (7b): yield 49%; FT IR (cm^{-1}) 2925, 2830 (C−H), 1609, 1566 (C−N), 978 (Re═O); ^{1}H NMR (DMSO-d_6) δ 1.96−2.10 (m, 1H), 2.28−2.33 (m, 1H), 3.19−3.27 (m, 2H), 3.75 (s, 6H), 3.73−3.77 (m, 2H), 6.95 (d, J = 8.7 Hz, 4H), 7.15 (d, J = 8.7 Hz, 4H). Anal. Calcd for $C_{19}H_{21}N_4O_3ReS_2$: C, 37.80; H, 3.51; N, 9.28. Found: C, 37.92; H, 3.67; N, 9.14.

[1-Methyl-3-[3-(3-methylthioureido)propyl]thioureato]oxorhenium(V) (7c). A solution of **4c** (0.15 g, 0.68 mmol) and ReO$_2$I(PPh$_3$)$_2$ (0.59 g, 0.68 mmol) in ethanol (20 mL) was heated at 60 °C for 15 min with a few drops of 2 N NaOH (pH ∼8). After cooling, the reaction mixture was left overnight in a refrigerator. The red crystalline product which formed was collected, washed with EtOH and CHCl$_3$, and dried. The crude product was purified by column chromatography (silica gel, CHCl$_3$/MeOH, 10:1) to give 0.12 g (42%) of **7c**: FT IR (cm^{-1}) 2918, 2847 (C−H), 1623, 1590 (C−N), 982 (Re═O); ^{1}H NMR (DMSO-d_6) δ 1.81−1.93 (m, 1H), 2.18−2.23 (m, 1H), 2.90−2.97 (m, 2H), 3.02 (s, 6H), 3.53−3.60 (m, 2H), 9.62 (s, 1H). Anal. Calcd for $C_7H_{13}N_4OReS_2$: C, 20.04; H, 3.12; N, 13.36. Found: C, 20.12; H, 3.14; N, 13.30.

X-ray Crystallography. An orange crystal of **7a** with dimensions of 0.12 × 0.33 × 0.40 mm was used for data collection. Intensity data were collected at room temperature on a Siemens P4 instrument. The crystal system and cell constants were determined by least-squares refinement of the values of 40 randomly selected reflections, of which 30 were high-θ reflections (>24°). Three check reflections measured every 97 reflections showed that no decay occurred during the data collection. The intensities were corrected for Lorentz and monochromator polarization and absorption (semiempirical method based on azimuthal scans). The structure was solved by direct and difference Fourier methods and refined by full-matrix least-squares procedures on F^2 using SHELXL 93. All non-hydrogen atoms were refined anisotropically. Peaks (Q) near N(3) (0.73 e Å^{-3}, 0.96 Å) and N(4) (0.59 e Å^{-3}, 0.96 Å) were observed in the Fourier difference map, but because the complex is neutral, protonation of only one N was possible. On the basis of the Q−N(3)−C (110.9 and 122.7°) and Q−N(4)−C (69.7 and 116.1°) bond angles and additional geometrical parameters (see Results), the H atom was assigned to N(3) and refined with an idealized bond distance (d(N−H) = 0.90 Å). All other H atoms were generated at calculated positions (d(C−H) = 0.96 Å). The H atoms were constrained using a riding model with isotropic thermal parameters that were 20% greater than the U(eq) of the atoms to which they were bonded. Crystal data and refinement parameters are reported in Table 1.

Results

Synthetic Chemistry. Scheme 1 illustrates the synthetic route utilized in the one-step, high-yield preparation of the dithiourea ligands **4** and **5**. The ligands were used directly in ligand exchange reactions with ReOCl$_3$(Me$_2$S)(OPPh$_3$) or ReO$_2$I(PPh$_3$)$_2$. Compounds **7a,b** were prepared by warming

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(18) Grove, D. E.; Wilkinson, G. *J. Chem. Soc. A* **1966**, 1224.
(19) Bryan, J. C.; Tulip, R. E.; Mayer, J. M. *Inorg. Chem.* **1987**, *26*, 2283.
(20) Ciani, G. F.; D'Alfonso, G.; Romiti, P. F.; Sironi, A.; Freni, M. *Inorg. Chim. Acta* **1983**, *72*, 29.

Table 1. Crystallographic Data for **7a**.

empirical formula	$C_{17}H_{17}N_4OReS_2$
crystal system	monoclinic
space group	$P2_1/c$
a (Å)	11.828(2)
b (Å)	8.605(2)
c (Å)	17.720(4)
β (deg)	92.98(3)
V (Å^3)	1801.1(7)
Z	4
fw	543.67
d (calc) (Mg/m^3)	2.01
abs coeff (mm^{-1})	6.99
radiation (λ (Å))	Mo Kα (0.7103)
T (K)	293(2)
min/max, transm	0.684/0.339
final R indices [$I > 2\sigma(I)$]	R1 = 0.035, wR2 = 0.090
R indices (all data)	R1 = 0.041, wR2 = 0.095

chelates **4a,b** with $ReOCl_3(Me_2S)(OPPh_3)$ in basic methanol solution. Initial attempts to obtain **7c** using this procedure were not successful. A black, insoluble solid that was probably $Re^{IV}O_2$, a disproportionation product of Re^V to Re^{IV} and Re^{VII}, formed immediately. Analytically pure **7c** was synthesized under basic conditions by ligand exchange from $ReO_2I(PPh_3)_2$ in good yield. Several attempts to prepare **6a** from **5a** using both precursors, $ReOCl_3(Me_2S)(OPPh_3)$ and $ReO_2I(PPh_3)_2$, failed.

Spectroscopy. The infrared spectra of **7a**−**c** show strong Re═O stretching bands at 978−984 cm^{-1}. The frequencies of these bands are characteristic of a metal−oxo stretch and are similar to those observed for the Re═O bands in several well-characterized $[Re^VO]^{3+}$ complexes.[21−25]

The ^{1}H NMR spectra of the Re complexes in DMSO-d_6 have one set of signals assignable to the alkyl and/or aryl portions of the ligand side chains, along with a set of four multiplets of 2:2:1:1 intensity attributable to hydrogen atoms of the propylene bridge. Only one singlet (3.75 ppm) for the two methoxy groups and two doublets of equal intensity (6.95 and 7.15 ppm; J = 8.7 Hz), assigned to the aromatic portion of the ligand, were observed for **7b**. Similarly, only one singlet (3.02 ppm) was found for the two methyl groups for **7c**. The ^{13}C NMR spectrum of **7a** showed only seven peaks (two for the alkane carbon atoms, one for the thiocarbonyl carbon atoms, and four for the aromatic carbon atoms). Thus, the NMR data were consistent with the presence of only one isomer, which is symmetrical on the NMR time scale.

X-ray Crystallography. Final atomic coordinates and a perspective drawing of the neutral complex molecule of **7a** are presented in Table 2 and Figure 1, respectively. Selected bond lengths and bond angles are listed in Table 3. The complex has a distorted square-pyramidal coordination geometry, with the N_2S_2 ligand coordinated at the four corners of the basal plane and the oxo ligand at the apex. The Re atom is displaced 0.82 Å above the basal plane toward the oxo group.

Table 2. Atomic Coordinates ($\times 10^4$) and Equivalent Isotropic Displacement Coefficients (Å^2 $\times$ 10^3) for **7a**

atom	x	y	z	U(eq)[a]
Re	603(1)	940(1)	3169(1)	20(1)
S(1)	−1315(2)	1490(3)	2855(1)	25(1)
S(2)	1226(2)	3379(3)	3607(1)	30(1)
N(1)	−388(6)	−801(8)	3501(4)	21(2)
N(2)	1412(7)	709(9)	4144(4)	25(2)
N(3)	−2386(6)	−912(8)	3574(4)	23(2)
N(4)	2408(6)	2509(8)	4957(4)	19(2)
O	1343(5)	420(8)	2428(3)	30(2)
C(1)	−1448(7)	−306(11)	3332(4)	20(2)
C(2)	−81(8)	−2119(11)	3994(5)	26(2)
C(3)	1181(8)	−2097(11)	4207(4)	24(2)
C(4)	1584(8)	−640(10)	4636(5)	25(2)
C(5)	1841(8)	2182(10)	4350(4)	23(2)
C(6)	−3510(7)	−471(11)	3347(5)	21(2)
C(7)	−3810(8)	51(15)	2633(5)	40(3)
C(8)	−4902(11)	517(19)	2448(6)	64(4)
C(9)	−5729(9)	396(15)	2954(6)	45(3)
C(10)	−5449(8)	−194(13)	3671(6)	35(2)
C(11)	−4338(8)	−615(11)	3867(5)	31(2)
C(12)	2868(9)	4023(10)	5048(5)	27(2)
C(13)	3483(8)	4708(11)	4493(5)	27(2)
C(14)	3975(10)	6114(11)	4602(6)	36(3)
C(15)	3877(9)	6910(12)	5281(6)	40(3)
C(16)	3246(9)	6261(11)	5843(6)	35(3)
C(17)	2755(9)	4844(12)	5726(5)	35(2)

[a] U(eq) is defined as one-third of the trace of the orthogonalized $\mathbf{U}_{ij}$ tensor.

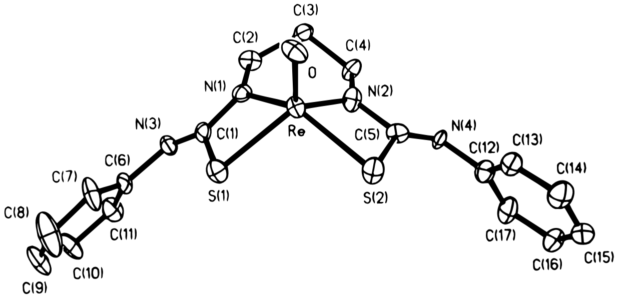

Figure 1. Perspective drawing of **7a** with 50% probability for the thermal ellipsoids.

Table 3. Selected Bond Lengths (Å) and Bond Angles (deg) for **7a**

Bond Lengths (Å)

Re−O	1.677(6)	N(1)−C(1)	1.343(11)
Re−N(1)	2.008(7)	N(2)−C(5)	1.406(11)
Re−N(2)	1.942(7)	N(3)−C(1)	1.317(11)
Re−S(1)	2.355(2)	N(3)−C(6)	1.421(12)
Re−S(2)	2.343(3)	N(4)−C(5)	1.269(11)
S(1)−C(1)	1.773(9)	N(4)−C(12)	1.418(11)
S(2)−C(5)	1.796(8)		

Bond Angles (deg)

O−Re−N(2)	114.6(3)	C(5)−S(2)−Re	80.6(3)
O−Re−N(1)	111.5(3)	C(1)−N(1)−C(2)	125.3(7)
N(2)−Re−N(1)	86.1(3)	C(1)−N(1)−Re	104.5(5)
O−Re−S(2)	109.3(3)	C(5)−N(2)−C(4)	121.6(7)
N(2)−Re−S(2)	70.4(2)	C(5)−N(2)−Re	107.1(5)
N(1)−Re−S(2)	138.6(2)	N(3)−C(1)−N(1)	126.5(8)
O−Re−S(1)	113.8(2)	N(3)−C(1)−S(1)	126.7(7)
N(2)−Re−S(1)	130.9(2)	N(1)−C(1)−S(1)	106.1(6)
N(1)−Re−S(1)	69.5(2)	N(4)−C(5)−N(2)	126.0(8)
S(2)−Re−S(1)	100.41(9)	N(4)−C(5)−S(2)	132.1(7)
C(1)−S(1)−Re	79.6(3)	N(2)−C(5)−S(2)	101.5(6)

Both coordinated N atoms (N_c), N(1) and N(2), are deprotonated. Because the complex is neutral, one of the N_u atoms must also be deprotonated. The solution spectra are consistent with this protonation state. In the solid, it is not so clear which N_u atom, N(3) or N(4), is deprotonated, N_u^-, or protonated, N_uH. N(3) and N(4) are within H-bonding distance of N(4) and N(3), respectively, of a symmetry-related molecule ($-x$, $-y$, $1-z$; N···N 2.945 Å; N−H···N 150.7°) (Figure 2), suggesting that the two N_u's share one proton. Peaks consistent with H atoms were observed in the Fourier difference map near both

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(21) Rao, T. N.; Adhikesavalu, D.; Camerman, A.; Fritzberg, A. R. *J. Am. Chem. Soc.* **1990**, *112*, 5798.

(22) Marzilli, L. G.; Banaszczyk, M. G.; Hansen, L.; Kuklenyik, Z.; Cini, R.; Taylor, A., Jr. *Inorg. Chem.* **1994**, *33*, 4850.

(23) Hansen, L.; Taylor, A., Jr.; Marzilli, L. G. *Metal-Based Drugs* **1995**, *2*, 105.

(24) Hansen, L.; Taylor, A., Jr.; Marzilli, L. G. *Metal-Baed Drugs* **1994**, *1*, 31.

(25) Hansen, L.; Cini, R.; Taylor, A., Jr.; Marzilli, L. G. *Inorg. Chem.* **1992**, *31*, 2801.

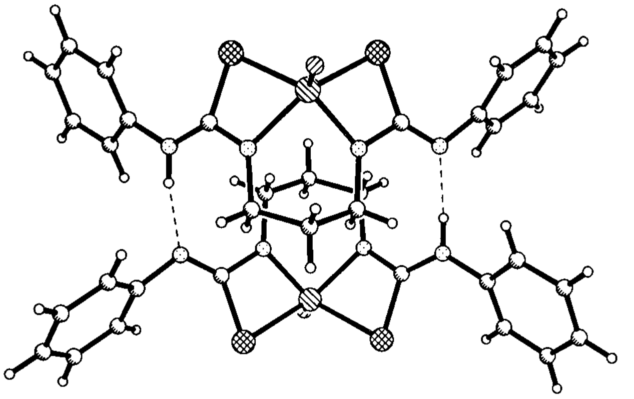


Figure 2. View of the two intermolecular H-bonds between symmetry-related pairs of complex molecules the crystal lattice of **7a**.

N(3) and N(4), and the difference in distance between the N(3)−C(1) and the N(4)−C(5) bond was not significant.

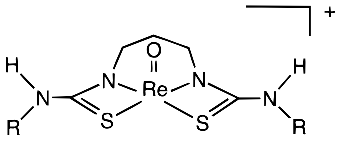
However, other data suggest that N(4) is N_u^-. The Re−N(2) bond distance found was significantly shorter than the Re−N(1) bond distance. The Re−N bond is long for a related bidentate thiourea ligand in which N_u is protonated, namely in ReO(TATU-Ph) (TATU-Ph = 1-phenyl-3-[2-((2-thioacetyl)-amino)ethyl]thioureato).[12] Furthermore, for **7a** the N_c−C distance (N(2)−C(5)) is significantly longer than the N_u−C (N(4)−C(5)) bond distance. In contrast, the N(1)−C(1) and N(3)−C(1) bond distances of **7a** and the N_c−C and N_uH−C bond distances of ReO(TATU-Ph)[12] fell within a narrow range (1.30(2)−1.36(2) Å). In the few examples of other transition metal complexes with thiourea coordinated in a bidentate manner, such similar distances are characteristic.[13−15] Because of the unusual bonding pattern in the Re−N(2)−[C(5)−S(2)]−N(4) fragment of **7a**, we conclude that N(4) is deprotonated and N(3) is protonated (Figure 2).

The N_c−C−S (106.1(6), 101.5(6)°) and N_u−C−S (132.1(7), 126.7(7)°) bond angles are severely distorted from the 120° expected from sp^2-hybridized C. But as a result of the narrowing of the N_c−C−S bond angle, the Re−S(thiocarbonyl) bond distances are normal. These bond distances are actually comparable to those observed in $M^V{=}O$ complexes with monodentate thiourea ligands (2.356(5)−2.311(7) Å)[7,8,10,26] despite the fact that they are part of a four-membered chelate ring in **7a**.

The metal and thiourea atoms are nearly coplanar, suggesting that the Re−S and Re−N bonds may have some π character. The mean deviations from the best fit planes of Re, S(1), N(1), N(3), C(1) and Re, S(2), N(2), N(4), C(5) were 0.077 and 0.027 Å, respectively. However, the two phenyl rings attached to N(3) and N(4) are tilted with respect to the N−C(S)−N planes and the N−C(Ph) bond distances are characteristic of single-bond distances. Therefore, there is no π overlap between the aromatic and the thiourea systems. However, each phenyl ring is tilted to a different degree (N(3), 41°; N(4), 56°). In the crystal lattice, the N(4) phenyl ring was partially stacked over the N(4) phenyl ring of a neighboring molecule ($1 - x$, $1 - y$, $1 - z$). There were no stacking interactions involving the N(3) phenyl ring. Thus, packing forces are probably responsible for differences in the C(Ph)−C(Ph)−N−C(tu) torsion angles between the halves of the complex (Supporting Information).

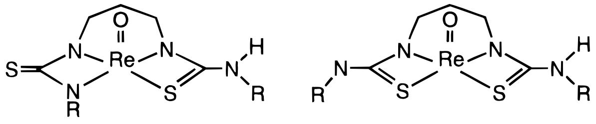
Discussion

On the basis of the established chemistry of $Re^V{=}O$ N_2S_2 complexes and of thiourea ligands, we expected that the DTU ligands would form square-pyramidal $Re{=}O(N_2S_2)(N_uH)_2$ monocation complexes. In support of this prediction, the NMR spectra of the complexes were consistent with mirror plane symmetry between the halves of the ligand and diastereotopic vicinal protons due to the presence of the oxo ligand on one side of the ligand coordination plane (**II**). However, elemental analyses of **7a**−**c** were consistent with the formulation as neutral compounds and the loss of three of the four dissociable NH protons. Loss of an NH proton upon complexation generally does not occur unless a metal−N bond is formed. The loss of three protons suggested two alternative explanations: First, the complexes have an N_3S donor set (**III**). In this case, the formation of a neutral complex could be understood but the reason for the simplicity of the NMR spectra was not obvious. Second, the complexes have an N_uH/N_u^- protonation state, an unusual situation since no other such species have been reported. However, rapid proton exchange between the two N_u sites would account for the simple NMR spectra. Therefore, the structure of one of the complexes was determined by X-ray diffraction methods.



N_2S_2

II



N_3S **N_2S_2**

III

The solid-state structure of **7a** revealed that the DTU ligands coordinate in the expected fashion with bidentate N,S coordination of both thiourea moieties. One thiourea was monodeprotonated at N_c; however, the second thiourea was deprotonated at both N_c and N_u. Double deprotonation of a bidentate N,S thiourea ligand is unprecedented and remarkable because the deprotonated N_u is three bonds away from the metal. In **7a**, deprotonation of N_u(4) affected the bonding pattern between the Re−N(2)−C(5)−[S(2)]−N(4) atoms compared to the bonding pattern in the other half of the molecule, and as a result the Re−N(2) bond distance was significantly shorter than the Re−N(1) bond distance. The Re−N(2)−C(5)−[S(2)]−N(4) atoms were also nearly coplanar. These observations suggest that the acidity of the N_u(4) proton is a result of a shift in electron density through an extended π system toward the high-valent Re(V) atom.

The distortions in the N_c−C−S and N_u−C−S bond angles observed for **7a** were similar to (but smaller than) those observed for ReO(TATU-Ph) (109.8(12), 105.5(11)°).[12] However, the Re−S(thiocarbonyl) bond distances in **7a** were found to be significantly shorter than those in ReO(TATU-Ph). The propylene bridge allows for a significantly larger N−Re−N bond angle (∼86°) compared to the analogous bond angles in ReO(TATU-Ph) (∼77°). These comparisons suggest that the TATU ligand (with five-, five-, and four-membered chelate rings) does not accommodate the small N_c−C−S bite angle of the bidentate thiourea moiety as well as the DTU ligand. The propylene bridge appears to be essential in the DTU-type ligands since the ethylene DTU ligand did not form $Re^V{=}O$ complexes.

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(26) Abram, U.; Muenze, R.; Hartung, J.; Beyer, L.; Kirmse, R.; Koehler, K.; Stach, J.; Behm, H.; Beurskens, P. T. *Inorg. Chem.* **1989**, *28*, 834.

The NMR results are consistent with the solid-state structure. The rapid interchange of the one proton between the two uncoordinated N's accounts for the spectral simplicity in several solvents. ^{1}H NMR spectra of **7b** recorded at 20 and −50 °C (in $CDCl_3$) were similar. Only one methoxy singlet and one set of the two doublets of equal intensity, assigned to the aromatic portion of the ligand, were observed. In methanol, the spectra of **7b** have signals consistent with one species (Suppporting Information). Two doublets assigned to the aromatic protons were present at 6.88 and 7.11 ppm. Addition of an excess of NaOD caused small shifts (<0.1 ppm). However, addition of 1 equiv of DCl caused large downfield shifts of the aromatic signals to 7.04 and 7.39 ppm. Separate signals for the protonated and deprotonated forms were not observed. Thus, no change in ligation occurred, and the shifts on protonation suggest that the N_uH/N_u^- neutral complex became the $(N_uH)_2$ monocation. The signals did not shift further with addition of a second equivalent of DCl. The absence of shift on addition of base indicates that deprotonation of the N_uH/N_u^- neutral complex to form a monoanion was not favorable. Also, methoxide or hydroxide did not coordinate detectably *trans* to the oxo group. Such coordination occurs for other types of $ReO(N_2S_2)$[27] and $ReO(NS)_2$[28,29] complexes.

In conclusion, the DTU ligand system forms small neutral or near-neutral $Re^V{=}O$ complexes. Protection/deprotection chemistry was not required in the syntheses. The synthetic methods are versatile; appropriately substituted isothiocyanates are commercially plentiful or can be prepared readily from primary amines. Although this is only the second class of multidentate chelating ligands to incorporate the thiourea moiety, we have found that this N,S bidentate chelating group can coordinate in a dideprotonated form in addition to the recently found monodeprotonated form.

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Supporting Information Available: Tables of crystal data and experimental parameters, bond distances, bond angles, selected torsion angles, anisotropic displacement coefficients, and H atom parameters and a view in $P2_1/c$ for **7a**, as well as a listing of ^{1}H NMR data for **7b** in CD_3OD (8 pages). Ordering information is given on any current masthead page.

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(27) Hansen, L.; Lipowska, M.; Taylor, A., Jr.; Marzilli, L. G. *J. Nucl. Med.* **1995**, *36*, 155P.

(28) Hansen, L.; Xu, X.; Yue, K. T.; Taylor, A., Jr.; Marzilli, L. G. *Inorg. Chem.* **1996**, *35*, 2785.

(29) Hansen, L.; Xu, X.; Yue, K. T.; Kuklenyik, Z.; Taylor, A., Jr.; Marzilli, L. G. *Inorg. Chem.* **1996**, *35*, 1958.