$CHCl_3$), R_f 0.27 in 2:1 ether–hexane) and **1b** (mp 156–157 °C, $[\alpha]^{23}{}_D$ +8.1° (c = 0.8, $CHCl_3$), R_f 0.25 in 2:1 ether–hexane).[18,19] Protostenediols **1a** and **1b** were separately converted to the corresponding 3-benzoyl-24,25-dihydro derivatives and treated with BF_3 at −78 °C in CH_2Cl_2 for 15 min. Each gave cleanly a 1:1 mixture of dihydroparkeol benzoate (**16**) and the C(20) diastereomer, which was separated by silica gel TLC ($AgNO_3$). The dihydroparkeol benzoate produced by rearrangement from **1a** or **1b** was found to be identical with an authentic sample of **16**.[20] The conversion of **1a** or **1b** to **16** confirms the successful synthesis of **1a** and **1b**. This synthesis contains a number of noteworthy steps including (1) enantioselective and efficient generation of **3**, (2) selective annulation of **3** to **4**, (3) use of the 14,15β-methylene group as a precursor of the 14β-methyl group and also as a control element for the specific introduction of the 17α side chain, (4) use of the allyl diazene rearrangement for generating the trans A/B (B-boat) arrangement, and (5) efficient elaboration of the A-ring substructure.[21]

Supplementary Material Available: Full spectral data on compounds **2–16** as well as other synthetic intermediates (32 pages). Ordering information is given on any current masthead page.

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Induced Internal Electron Transfer Reactivity of Tetrathioperrhenate(VII): Synthesis of the Interconvertible Dimers $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4$ and $[Re_2(\mu\text{-}SS_2CNR_2)_2(S_2CNR_2)_3][O_3SCF_3]$ (R = Me, *i*-Bu)

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Received March 19, 1990

Rhenium sulfides, e.g., ReS_2 and Re_2S_7, have long been recognized for their hydrogenation and dehydrogenation reactivity.[1] Periodic trends in catalytic hydrodesulfurization (HDS) reveal rhenium sulfur systems to have high activity.[2] However, discrete, soluble rhenium sulfur species have not received as much attention as have group VI sulfide systems.[3] The tetrathiometalate anions of V, Mo, and W (VS_4^{3-}; MoS_4^{2-}; WS_4^{2-}), which possess fully oxidized (d^0) metal centers and fully reduced (S^{2-}) sulfide ligands, undergo internal redox upon reacting with external oxidants.[4] In these reactions bound sulfide ions (S^{2-}) serve as the reductant forming disulfide (S_2^{2-}) concomitant with reduction of the metal center. Conspicuously, ReS_4^- is the only soluble tetrathiometalate whose chemistry in this regard has not been explored. Here we report that tetraalkylthiuram disulfide, acting as an *oxidant*, induces a dramatic and unprecedented 3e⁻ *reduction* of the Re(VII) center of ReS_4^-. Moreover, the resultant Re(IV)–Re(IV) dimer, $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4$ (**1**), undergoes induced internal electron transfer in the presence of tetraalkylthiuram disulfide and a Lewis acid, leading to the Re(III)–Re(III) dimer $Re_2(\mu\text{-}SS_2CNR_2)_2(S_2CNR_2)_3^+$ (**2**), which contains two trithiocarbamate ligands. The interconversion of **1** and **2** involves induced redox in both directions and can be effected with high regioselectivity.

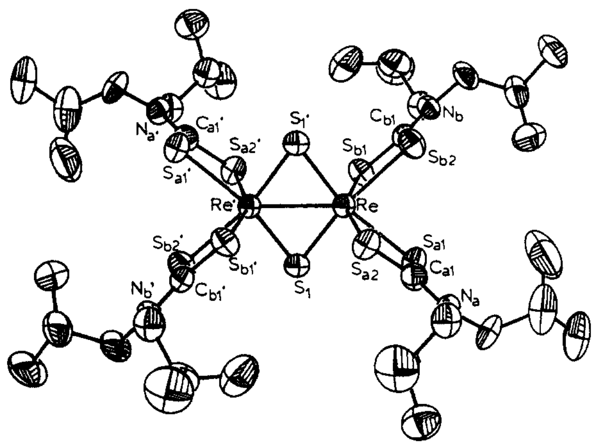

Figure 1. A perspective drawing of $Re_2(\mu\text{-}S)_2(S_2CN(C_4H_9)_2)_4{\cdot}2OC_4H_8$ (**1b**) (OC_4H_8 not shown) with non-hydrogen atoms represented by thermal vibration ellipsoids drawn to encompass 50% of their electron density. For clarity, the carbon atoms of the isobutyl groups are not labeled.

The reaction of red-violet $[Et_4N][ReS_4]$[5] with tetraalkylthiuram disulfides in acetonitrile gives green products with the general formula $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4$ (**1**; R = Me, **1a**; *i*-Bu, **1b**). Tetraalkylthiuram disulfides, conventionally used as *oxidants*, in this reaction induce a 3e⁻ internal *reduction* of the Re(VII) metal center to give the neutral Re(IV) dimer. The coordinated sulfide (S^{2-}) serves as the reductant for both the tetraalkylthiuram disulfide and the Re(VII). Elemental sulfur is produced, presumably from coordinated sulfide. Analytical and spectroscopic data[6] are consistent with the formulation $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4$.

Dark green rectangular crystals were obtained by layering hexane over a THF solution of **1b** at −20 °C. The single-crystal X-ray diffraction study[7] of **1b** reveals a crystallographically centrosymmetric dinuclear structure (Figure 1) containing distorted edge-shared bioctahedra.[8] Each rhenium atom is coordinated to two bridging sulfide and two chelating dithiocarbamate ligands. The Re–Re distance is short, 2.546 (1) Å, with the Re

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(6) Anal. Calcd for **1b**: C, 34.48; H, 5.79; N, 4.47; S, 25.57; Re, 29.70. Found: C, 34.49; H, 5.82; N, 4.49; S, 26.05; Re, 29.48. FAB-MS displayed parent ion peaks and fragmentation patterns corresponding to the dinuclear formulation. Infrared spectra (KBr pellet): bands at 420–440 and 330–350 cm^{-1} suggesting a bridging Re–S unit and no band attributable to S–S stretching. UV–vis spectra had low-energy bands at 750 and 650 nm. ^1H NMR (22 °C, $CDCl_3$, 360 MHz): δ 2.843 (s, 1), 3.358 (s, 1).

(7) Data collection and structure refinement by Crystalytics Co., Lincoln, NE. **1b** crystal data: $Re_2(\mu\text{-}S)_2(S_2CN(i\text{-}Bu)_2)_4{\cdot}2OC_4H_8$, monoclinic, $P2_1/c$, (No. 14), a = 11.084 (2) Å, b = 13.815 (3) Å, c = 19.945 (4) Å, β = 92.23 (2)°, Z = 2, V = 3052 (2) Å³, D_{calcd} = 1.522 g cm⁻³. The structure was refined (301 parameters) to R_1 = 0.043, R_2 = 0.051, 3268 independent reflections. Bond distances (Å): Re–Re′, 2.546 (1); Re–S_{a1}, 2.511 (3); Re–S_{a2}, 2.430 (3); Re–S_1, 2.275 (3). Bond angles (deg) of Re_2S_2 core: Re–S_1–Re′, 68.1 (1); S_1–Re–S_1′, 111.9 (1); S_{a1}–Re–S_{a2}, 70.6 (1).

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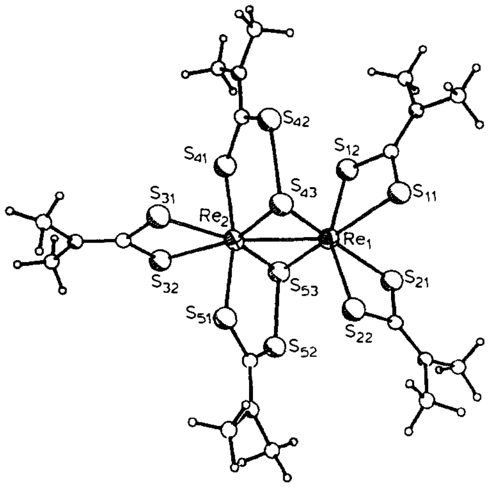

Figure 2. A perspective drawing of $[Re_2(\mu\text{-}SS_2CN(CH_3)_2)_2(S_2CN(CH_3)_2)_3][SO_3CF_3]\cdot CH_3CN$ (**2a**) (SO_3CF_3 anion and CH_3CN of crystallization not shown). Non-hydrogen atoms are represented by thermal vibration ellipsoids drawn to encompass 50% of their electron density; hydrogen atoms are represented by arbitrarily small spheres not representative of their thermal motion. For clarity, carbon, nitrogen, and hydrogen atoms are not labeled.

atoms displaced from the S_6 pseudooctahedral centroid toward each other, consistent with multiple metal–metal bonding. A similar phenomenon is observed in rhombohedral ReS_2, where the shortest Re–Re distance is 2.54 Å.[9] When **1b** is viewed down the Re–Re axis, planes of sulfur atoms (one μ-S and four sulfur atoms from two dithiocarbamate ligands) are discerned above and below the two rhenium atoms, again reminiscent of ReS_2. The arrangement of chelating dithiocarbamate ligands in **1b** defines a meso diastereoisomer with Λ and Δ conformations at the two metal centers.[10,11]

Reaction of $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4$ (**1a**) in CH_2Cl_2 with excess trimethylsilyl triflate ($Me_3SiO_3SCF_3$) in the presence of 1 equiv of tetraalkylthiuram disulfide leads to a color change from green to red with precipitation of **2a** in 70% yield.[12] The single-crystal X-ray diffraction study[13] of **2a** reveals the cationic dimer $[Re_2(\mu\text{-}SS_2CNR_2)_2(S_2CNR_2)_3][O_3SCF_3]$ in Figure 2, which contains three chelating dithiocarbamate and two chelating and bridging trithiocarbamate ligands.[14] The structure contains a $S_4Re(\mu\text{-}S)_2ReS_4$ core with a C_2 symmetry axis through the two rhenium centers. The Re–Re distance is 2.573 (2) Å. The ^1H NMR spectrum (five singlet methyl resonances in CD_3CN)[15] is consistent with the solid-state structure which has precedent in the chemistry of Os.[15] The generation of two bridging trithiocarbamates in this reaction involves the formation of S–S bonds between the bridging sulfides of the $Re_2(\mu\text{-}S)_2$ core and dithiocarbamate ligands. As in **1**, an intriguing structural feature of **2a** is its nearly layered arrangement of Re and S atoms.

Complex **2a** regenerates complex **1a** when treated with 1 equiv of $LiEt_3BH$ in CH_2Cl_2, or when heated in morpholine (90 °C), in tetrahydroquinoline (110 °C), or under pressure of H_2 in $CD_3CN\text{-}CD_2Cl_2$, 1:1 ratio (475 psi, 75 °C, 75 min). These reductants cause the oxidation of Re(III) to Re(IV) with the coordinated bisulfide ligand serving as the internal oxidant. This reaction is one of the few examples of an induced internal electron transfer that involves an external *reductant* causing the *oxidation* of a metal center.

The regioselectivity of the interconversion of **1a** and **2a** was investigated by ^1H NMR, mass spectroscopy, and isotopic labeling. The reaction of $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4\text{-}d_{24}$ ($R = CD_3$), **1a**-d_{24}, with perprotio tetramethylthiuram disulfide and $Me_3SiSO_3CF_3$ gives the Re(III) dimer, **2a**-d_{24}, with a ^1H NMR spectrum showing only two (3.753 and 3.329 ppm) of the five singlets. The reaction of the perprotio $Re_2(\mu\text{-}S)_2(S_2CNR_2)_4$ (**1a**) with perdeuterio tetramethylthiuram disulfide and $Me_3SiSO_3CF_3$ gives **2a**-d_6 with a ^1H NMR spectrum consisting of five resonances. However, the intensities of the 3.753 and 3.329 ppm resonances are half those of the other three. These results are consistent with the regioselective incorporation of *one* dimethyldithiocarbamate fragment from the tetramethylthiuram disulfide oxidant as either the trithiocarbamate or one of the equivalent pair of dithiocarbamate ligands.

The back reaction, **2a** going to **1a**, was similarly regioselective. Complexes **2a**-d_{24} and **2a**-d_6 were reacted with $LiEt_3BH$ to give **1a**. The dimethyldithiocarbamate salt produced in this reaction was extracted into water, oxidized to the tetramethylthiuram disulfide, and analyzed by mass spectrometry for deuterium incorporation. In each case the mass spectrum showed parent ions of *m/e* 240, 246, and 252 in a 1:2:1 ratio for $[S_2CN(CH_3)_2]_2$, $(CH_3)_2NCS_2\text{-}S_2CN(CD_3)_2$, and $[S_2CN(CD_3)_2]_2$, respectively; ions of *m/e* 120 and 126 were observed in a 1:1 ratio for $S_2CN(CH_3)_2$ and $S_2CN(CD_3)_2$, respectively. These results are consistent with the conversion of **2a** to **1a** via a reaction that eliminates the same dimethyldithiocarbamate that was added or its symmetry equivalent. Although it is not known which dithiocarbamate is added or eliminated,[15] we favor the trithiocarbamate ligand as the reactive entity in this reaction.

The transformation of **1** to **2** involves an overall, formal two-electron reduction of the neutral Re(IV) dimer with the concomitant formation of two S–S bonds. This reaction proceeds in the presence of tetraalkylthiuram disulfide and the Lewis acid trimethylsilyl cation or with LiCl but not with protic acids such as $HBF_4\cdot OEt_2$. The interconversion of **1** and **2** under acid/hydrogenation conditions may mimic patterns in dehydrogenation/hydrogenation reactions of some solid-state metal sulfides.

In summary, three induced internal electron transfer reactions involving rhenium are described. The resultant new, discrete, soluble, rhenium dimers contain Re(IV)–Re(IV) and Re(III)–Re(III) multiple bonds, have layered molecular S–Re–S structures, and exhibit acid/H_2 reactivities of significant interest with respect to their layered solid-state counterparts. The interconversion of the two dimers occurs with great regioselectivity.

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(12) **2a**: $[Re_2(\mu\text{-}SS_2CN(CH_3)_2)_2(S_2CN(CH_3)_2)_3][O_3SCF_3]$. Anal. Calcd for $C_{15}H_{30}N_5O_3F_3S_{13}Re_2$: C, 15.34; H, 2.57; N, 5.96; F, 4.85. Found: C, 15.82; H, 2.66; N, 5.95; F, 4.75. ^1H NMR (22 °C, CD_3CN, 360 MHz): δ 3.753 (s, 1), 3.329 (s, 1), 3.231 (s, 1), 3.202 (s, 1), 2.861 (s, 1).

(13) Data collection and structure refinement by Crystalytics Co., Lincoln, NE. **2a**: crystal data: $[Re_2(\mu\text{-}SS_2CNMe_2)_2(S_2CNMe_2)_3][O_3SCF_3]\cdot CH_3CN$, triclinic, $P\bar{1}$ (No. 2), $a = 14.238$ (4) Å, $b = 11.476$ (4) Å, $c = 14.977$ (5) Å, $\alpha = 112.28$ (2)°, $\beta = 117.70$ (2)°, $\gamma = 89.14$ (2)°; $Z = 2$, $V = 1966$ (1) Å^3, $D_{calcd} = 2.075$ g cm^{-3}. The structure was refined to $R_1 = 0.057$, $R_2 = 0.064$, 2983 independent reflections. Selected bond distances (Å): $Re_1\text{–}Re_2$, 2.573 (2); $Re_1\text{–}S_{11}$, 2.484 (9); $Re_1\text{–}S_{12}$, 2.421 (6); $Re_1\text{–}S_{43}$, 2.294 (6); $Re_1\text{–}S_{53}$, 2.319 (8); $S_{42}\text{–}S_{43}$, 2.264 (7); $S_{52}\text{–}S_{53}$, 2.194 (7). Selected bond angles (deg) of Re_2S_2 core: $Re_1\text{–}S_{43}\text{–}Re_2$, 68.0 (2); $Re_1\text{–}S_{53}\text{–}Re_2$, 68.9 (2); $S_{43}\text{–}Re_1\text{–}S_{53}$, 110.1 (3); $S_{43}\text{–}Re_2\text{–}S_{53}$, 113.0 (3).

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Acknowledgment. We thank Scott Farina for the synthesis of the perdeuterio tetramethylthiuram disulfide.

Supplementary Material Available: Tables of atomic coordinates and thermal parameters and full list of bond lengths and bond angles for $Re_2(\mu\text{-}S)_2(S_2CN(C_4H_9)_2)_4\cdot 2OC_4H_8$ (**1b**) and $[Re_2(\mu\text{-}SS_2CN(CH_3)_2)_2(S_2CN(CH_3)_2)_3][SO_3CF_3]\cdot CH_3CN$ (**2a**) (20 pages); full list of observed and calculated structure factors for **1b** and **2a** (30 pages). Ordering information is given on any current masthead page.

Oxidation-State Assignments for Galactose Oxidase Complexes from X-ray Absorption Spectroscopy. Evidence for Cu(II) in the Active Enzyme

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Galactose oxidase, a copper metalloenzyme secreted by the fungus *Dactylium dendroides*, catalyzes the oxidation of primary alcohols to aldehydes and couples this reaction to the reduction of dioxygen to hydrogen peroxide:[1]

$$RCH_2OH + O_2 \rightarrow RCH{=}O + H_2O_2$$

Both the alcohol oxidation and the O_2 reduction half-reactions are two-electron redox processes, yet galactose oxidase contains a single copper atom and no additional metal ions and thus is unusual in its ability to catalyze two-electron redox chemistry at a mononuclear active site. The mechanism of catalysis has remained elusive, in part because of the variability exhibited by the native enzyme prepared according to published procedures.[2] Recently it has become possible to prepare stable, homogeneous and well-defined redox modifications of galactose oxidase for the first time, making available reductively inactivated, oxidatively activated, and a substrate complex as pure forms.[3] This recent work using homogeneous redox forms of galactose oxidase has demonstrated that it is the reductively inactivated enzyme that gives rise to the type 2 Cu EPR signal previously reported for this enzyme, and that this signal is absent in oxidatively activated galactose oxidase, even when redox agents have been removed. This is in agreement with the original report of this perplexing behavior[4] and demonstrates that the active form contains a unique EPR-silent oxidized copper complex.

Several structural proposals have been advanced to account for the unusual two-electron redox activity of galactose oxidase and the distinctive EPR behavior. The first, based on early results, was the plausible proposal of a formal Cu(III) oxidation state involved in a two-electron redox couple: $[Cu(III) + 2e^- \leftrightarrow Cu(I)]$.[4] In this model, the reductively inactivated enzyme contains Cu(II), which is oxidized to a formal Cu(III) state on activation, thus accounting for the loss of the EPR signal. A second proposal required that the metal ion be redox inactive, mediating electron transfer between substrate and O_2 while remaining in the cupric oxidation state.[5] According to the third proposal, activation is associated with protein-centered oxidation in which case the oxidatively activated galactose oxidase would contain Cu(II) and a stable organic radical. Spin coupling of two $S = {}^1/_2$ systems could then account for the EPR-silent character of the oxidized enzyme.[3] This proposal is consistent with spectroscopic evidence for Cu(II) in the active enzyme obtained from CD spectroscopy and from a comparison of ligand-to-metal charge-transfer spectra for the N_3^- adducts of oxidatively activated and reductively inactivated galactose oxidase. Recently a fourth model has been proposed in which a pyrroloquinoline quinone cofactor is associated with a Cu(I) active site in the oxidatively activated form of the protein.[6] A definitive assignment of the copper oxidation state in each accessible enzyme form is critical for distinguishing between these structural proposals. We report here X-ray absorption near-edge structure (XANES) spectra for each of the available pure redox modifications of galactose oxidase[11] and the copper oxidation-state assignment derived from each.

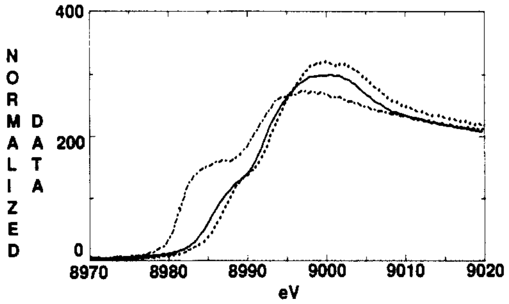

Figure 1. Normalized XANES spectra of oxidatively activated (—), reductively inactivated (---), and substrate (-·-) complexes of galactose oxidase. All samples were prepared according to ref 3.

XANES spectra are the structured absorption features that occur over approximately 50 eV in the region of a core-level electronic transition. In general, XANES is sensitive to oxidation state, coordination geometry, ligation type, and bond lengths of the absorbing site, making it a valuable structural probe for metal complexes. Cu(I) XANES spectra are readily distinguished by an intense resolved shoulder at ca. 8984 eV, below the range where more oxidized Cu absorbs. Previous work has demonstrated the utility of XANES, and in particular this Cu(I) feature, in determining Cu oxidation states.[7] Cu(III) XANES spectra are shifted by several electronvolts to higher energy relative to Cu(II),[8] probably due to shorter bond lengths for Cu(III) relative to Cu(II).[9] Blumberg et al. previously reported XANES spectra for galactose oxidase[8] and interpreted these as evidence against the presence of Cu(III) in the oxidatively activated enzyme.

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(10) XANES spectra were measured at the Stanford Synchrotron Radiation Laboratory (SSRL) beam line 4-1 and the National Synchrotron Light Source (NSLS) beam lines X-9A and X11A. Samples were placed in Mylar-windowed Lucite cuvettes at 10 (SSRL) or 77 K (NSLS) and data measured as fluorescence excitation spectra by using a multielement Ge detector array (SSRL) or an ionization chamber (NSLS). Spectra were normalized by subtraction of a polynomial and multiplication by a scale factor so as to give best agreement with tabulated X-ray cross sections (G. S. Waldo, J. E. Penner-Hahn, submitted for publication). X-ray energies were calibrated by reference to a Cu foil (first inflection point of foil 8980.3 eV). Spectra measured under different conditions are identical apart from minor differences in energy resolution [Si(220) monochromator crystals at SSRL vs Si(111) crystals at NSLS].

(11) The different redox states of galactose oxidase were prepared as described in ref 3 and were characterized by their EPR spectra measured on frozen samples in EXAFS sample cells.

0002-7863/90/1512-6433$02.50/0