However, in wet tetrahydrofuran or toluene, the reaction takes a different course: $LMo^{V}O(OH)(SPh)$ is detected directly via its EPR spectrum (g, 1.953; $a(^{95,97}Mo)$, 43.3×10^{-4} cm^{-1}; $a(^{1}H)$, 13.1×10^{-4} cm^{-1} in toluene; cf. refs 11 and 12). This species cannot be generated from preformed $[LMo^{V}O(SPh)]_2O$ under the same conditions, and the reaction would appear to involve an intermediate aquo–Mo(IV) complex:

$$LMo^{IV}O(OH_2)(SPh) + LMo^{VI}O_2(SPh) \rightarrow 2LMo^{V}O(OH)(SPh)$$

Certainly, $LMo^{V}O(OH)(SPh)$ can be trapped oxidatively as $LMo^{VI}O_2(SPh)$ with O_2 in 85% isolated yield. Water, not dioxygen, is the source of the oxo ligand: use of $H_2{}^{18}O$ (95 atom % ^{18}O) under anaerobic conditions with a prolonged incubation at the Mo^{V} level followed by admission of $^{16}O_2$ provides material enriched with 80 atom % ^{18}O.[14] Use of $H_2{}^{17}O$ (51.5 atom % ^{17}O) leads to clearly resolved ^{17}O structure in the EPR spectrum of the $LMo^{V}O(OH)(SPh)$ intermediate ($a(^{17}O)$, ca. 7×10^{-4} cm^{-1}; cf. ref 15). The two-electron Mo^{VI} to Mo^{IV} step is slower than the one-electron Mo^{IV} to Mo^{V} step preventing direct access to the putative $LMo^{IV}O(OH_2)(SPh)$ intermediate. In the presence of dioxygen and an excess of PPh_3, production of $OPPh_3$ is catalytic in Mo. Initial experiments indicate that at least 100 turnovers are possible with 98% isolated yields of $OPPh_3$.[16]

We have also achieved the first isolation of a dioxo–Mo(V) complex by the one-electron reduction of $LMoO_2(SPh)$. Estimates of the relevant one-electron couples in MeCN suggested that the right-hand side is favored in the following equilibrium:

$$LMo^{VI}O_2(SPh) + CoCp_2 \Leftrightarrow [LMo^{V}O_2(SPh)]^- + [CoCp_2]^+ \qquad K, \text{ ca. } 10^3$$

In acetonitrile, mixing of the reactants on the left-hand side leads to the rapid precipitation of green, microcrystalline, air-sensitive $[CoCp_2][LMo^{V}O_2(SPh)]$ (Cp = η^5-$C_5H_5^-$).[17] Isotope (^{18}O) labeling studies unambiguously identify a strong ν(MoO) band at 767 cm^{-1} in the anion and provide evidence for a second ν(MoO) band at 864 cm^{-1}, the assignment of which is complicated by interfering $[CoCp_2]^+$ and $^-$SPh bands. These values are extremely low in energy relative to those observed in $LMo^{VI}O_2(SPh)$ (922 and 889 cm^{-1}) and are consistent with the weakening of the Mo–O bonds expected due to population of the three-center π^* component of a *cis*-MoO_2 bonding scheme. In MeCN, cyclic voltammetry reveals the separate and characteristic $Mo^{VI}O_2/Mo^{V}O_2$ and $[CoCp_2]^+/CoCp_2$ couples associated with the component ions.

Dissolution of $[CoCp_2][LMo^{V}O_2(SPh)]$ in CH_2Cl_2 at room temperature initially produces a broad EPR signal (g, 1.920; $a(^{95,97}Mo)$, 41×10^{-4} cm^{-1}; $W_{1/2}$, 1 mT) characteristic of $[Mo^{V}O_2]^+$ centers.[11,12] Over time, the signal is replaced by that of the conjugate acid $LMo^{V}O(OH)(SPh)$ via reaction with trace H_2O. Upon freezing this solution at 77 K, the highly anisotropic spectrum of $[LMo^{V}O_2(SPh)]^-$ (g values; 1.991, 1.931, 1.843) appears, presumably due to the equilibrium being shifted toward the conjugate base by freezing out of H_2O.

Dioxygen rapidly and quantitatively oxidizes $[LMo^{V}O_2(SPh)]^-$ to $LMo^{VI}O_2(SPh)$. Reaction of $[LMo^{V}O_2(SPh)]^-$ with Me_3SiCl produces $LMo^{V}O(OSiMe_3)(SPh)$ in 92% isolated yield. When these reactions are performed on ^{18}O labeled anion *there is no significant loss of the label in the products.* The related $LMo^{V}O(OSiMe_3)(SCH_2Ph)$ complex may be similarly produced and has been characterized by X-ray crystallography.[18] In turn, $LMoO(OSiMe_3)(SPh)$ can be reduced to $LMo^{IV}O(SPh)(py)$ (Scheme II) by reaction with $CoCp_2$. Notably, we have been unable to observe any two-electron (i.e., oxygen atom transfer) chemistry with $[LMo^{V}O_2(SPh)]^-$. This may be the reason that $[Mo^{V}O_2]^+$ centers have never been detected during enzyme turnover.

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(14) Under anaerobic conditions, tetrahydrofuran (10 mL) and $H_2{}^{18}O$ (0.16 mL, 9.0 mmol, 95 atom % ^{18}O) were added to a mixture of $LMoO_2$(SPh) (0.240 g, 0.45 mmol) and PPh_3 (0.062 g, 0.24 mmol). After stirring for 7 h, $^{16}O_2$ was bubbled through the solution which rapidly turned from dark-green to dark-brown in color. Column chromatography (silica/toluene in air) yielded a major dark brown fraction, which was collected and evaporated to dryness. Recrystallization from CH_2Cl_2/MeOH gave a 76% yield of 80 atom % ^{18}O-enriched $LMoO_2$(SPh) (enrichment estimated by simulation of EI mass spectra). The infrared spectrum of the sample exhibited at least six bands and shoulders assignable to the $^{16}O^{16}O$, $^{18}O^{16}O$, and $^{18}O^{18}O$ isotopomers.

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(16) A mixture of $LMoO_2$(SPh) (0.05 g, 0.094 mmol) and PPh_3 (2.45 g, 9.4 mmol) in tetrahydrofuran (20 mL) and water (0.34 mL, 20 mmol) was stirred at 40 °C while being continuously purged with oxygen. Thin-layer chromatography revealed the quantitative conversion of PPh_3 to $OPPh_3$ after 10 h; workup permitted the isolation of $OPPh_3$ in 98% yield. The reaction does not occur in the absence of catalyst.

(17) A solution of cobaltocene (0.14 g, 0.74 mmol) in dry, deoxygenated MeCN (10 mL) was added to $LMoO_2$(SPh) (0.20 g, 0.37 mmol), and the mixture was stirred for 0.25 h. Green microcrystals were filtered off, washed with MeCN, and dried under vacuum. The yield of $[CoCp_2][LMoO_2(SPh)]$ was 0.19 g, 70%. Anal. Calcd for $C_{31}H_{37}BCoMoN_6O_2S$: C, 51.47; H, 5.16; N, 11.62; S, 4.43. Found: C, 51.23; H, 5.28; N, 11.90; S, 4.33. Cyclic voltammetry (MeCN, 0.1 M Bu_4NPF_6). $E_{1/2}$ −1.05 (Mo^{VI}/Mo^{V}), −1.23 ($CoCp_2^+/CoCp_2$), −2.16 V vs Ag/$AgNO_3$ (0.01 M).

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An Oxothio–Molybdenum(VI) Complex Stabilized by an Intramolecular Sulfur–Sulfur Interaction: Implications for the Active Site of Oxidized Xanthine Oxidase and Related Enzymes

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The oxothio–molybdenum(VI) active site proposed[1] for oxidized xanthine oxidase and related enzymes is supported by EXAFS studies[2] and, indirectly, by strong EPR evidence for $[Mo^{V}OS]^+$ and $[Mo^{V}O(SH)]^{2+}$ centers in enzyme[1,3d] and model systems.[3,4] However, $[MoOS]^{2+}$ complexes are extremely rare and are generally quite unstable.[5] Thus, the synthesis of a model for the

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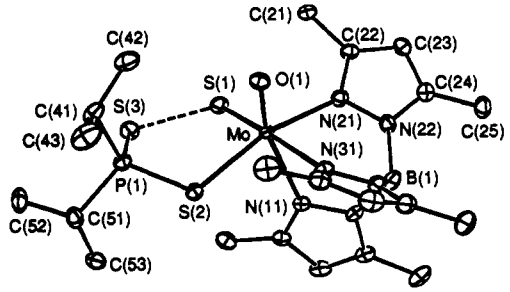


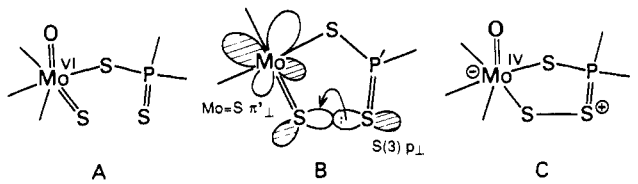
Figure 1. Molecular structure of **3**. Bond distances (Å) and angles (deg) include the following: Mo–O(1) 1.702 (4), Mo–S(1) 2.227 (2), Mo–S(2) 2.431 (2), Mo–N(11) 2.388 (5), Mo–N(21) 2.204 (5), Mo–N(31) 2.280 (6), S(1)–S(3) 2.396 (3), P(1)–S(2) 2.052 (2), P(1)–S(3) 2.007 (3) and S(1)–Mo–S(2) 92.5 (1), O(1)–Mo–S(1) 102.4 (2), O(1)–Mo–S(2) 100.9 (1), Mo–S(1)–S(3) 115.5 (1), S(1)–S(3)–P(1) 98.1 (1), S(2)–P(1)–S(3) 113.7 (1).

$[MoOS]^{2+}$ enzyme center remains a significant and unmet challenge, one frustrated by the reduction of Mo(VI) by the formally S^{2-} thio ligand and the reactivity of the thio ligand itself (vide infra). We report here the characterization of an octahedral $[MoOS]^{2+}$ complex and crystallographic evidence for the stabilization of the thio ligand through a weak intramolecular sulfur–sulfur interaction. This work bears directly on the very reactive nature of the $[MoOS]^{2+}$ moiety and its possible stabilization in enzyme systems.

Oxygen atom transfer to the oxo–molybdenum(IV) complex $\{HB(Me_2pz)_3\}MoO(\eta^2\text{-}S_2PPr^i_2)$ [**1**, $HB(Me_2pz)_3^-$ = hydrotris(3,5-dimethyl-1-pyrazolyl)borate] produces the dioxo–molybdenum(VI) complex $\{HB(Me_2pz)_3\}MoO_2(\eta^1\text{-}SP(S)Pr^i_2)$ (**2**).[6] Similarly, sulfur atom transfer from propylene sulfide to **1** results in the formation of the oxothio–molybdenum(VI) complex $\{HB(Me_2pz)_3\}MoOS(\eta^1\text{-}SP(S)Pr^i_2)$ (**3**).[7] The infrared spectrum of **3** is characterized by bands due to the $HB(Me_2pz)_3^-$ and $S_2PPr^i_2^-$ ligands, a low-energy ν(Mo=O) band reflecting a considerably weakened Mo=O bond (930 vs 960 cm^{-1} for **1**) and a band assigned to the Mo=S fragment (465 cm^{-1}). ^1H NMR spectroscopy reveals that molecules of **3** are chiral with C_1 symmetry. The electronic spectrum exhibits bands due to S → Mo LMCT transitions, consistent with a thio–molybdenum(VI) species.

An X-ray diffraction study[8] of **3** reveals a distorted octahedral complex composed of the tridentate $HB(Me_2pz)_3^-$ ligand, a relatively[6b,9] long terminal oxo ligand (Mo–O(1) = 1.702 (4) Å), and a novel fragment formed by weakly associated thio and $\eta^1\text{-}S_2PPr^i_2^-$ ligands. The short Mo–S(1) bond distance of 2.227 (2) Å is consistent with significant π bonding between these atoms, as is the case with thio–molybdenum(IV–VI) complexes (Mo=S range 2.09–2.13 Å[10]) and non-oxo complexes such as $\{HB(Me_2pz)_3\}MoCl(S_4)$ (av Mo–S = 2.19 Å[11]). However, complex **3** is the first octahedral oxo–molybdenum complex to reveal such a short Mo–S distance. The Mo–S(2) bond distance of 2.431 (2) Å is slightly shorter than Mo–S bonds in related complexes.[6b] The lengthening of the Mo–N(n1) bonds in the order Mo–N(11) > Mo–N(31) > Mo–N(21) indicates that the trans influence exerted by the Mo–O/S bonds increases in the order Mo–O(1) > Mo–S(1) > Mo–S(2). The S(1)–S(3) distance of 2.396 (3) Å is extremely long compared to sulfur–sulfur single bonds in related Mo complexes (2.0–2.10 Å[12–16]) and elemental sulfur[17] but is comparable to the long (2.39 Å) S···S partial[18a] bond in the dithionite ion $[O_2SSO_2]^{2-}$,[18b] a species which is susceptible to S···S bond cleavage.[18c] The P–S(3) bond is also significantly shorter than the P–S(2) bond.

Extreme canonical structures **A** and **C**, formal $[Mo^{VI}OS(\eta^1\text{-}S_2PPr^i_2)]^+$ and $[Mo^{IV}O(\eta^2\text{-}S_3PPr^i_2)]^+$ complexes, respectively, may be written for **3**; the actual structure may be described as a



A B C

resonance hybrid dominated by **A**.[19] In molecular orbital terms, **3** is most appropriately described as an oxothio–molybdenum(VI) complex stabilized by a dative interaction involving the filled donor S(3) $p_\perp$ orbital and the acceptor $\pi^*_\perp$ LUMO of the $[MoOS]^{2+}$ fragment (**B**, the view is along the Mo=O bond; ⊥ is defined with respect to this bond). Such an interaction accounts for the long S(1)–S(3) distance, the S(1)–S(3)–P(1) angle of 98.1 (1)° and, through population of the Mo=S π^* orbital, the lengthening of the Mo=S(1) bond relative to those more typical of thio–molybdenum complexes.[10] The reaction of the Mo=S π^* LUMO with solution species (e.g., "S" to form S_x^{2-} ligands[20]) or ligands (e.g., $S_2PR_2^-$) may indeed dominate the chemistry of the $[MoOS]^{2+}$ fragment. Thus, while an attractive strategy for the synthesis of $[MoOS]^{2+}$ species, sulfur atom transfer to oxo–molybdenum(IV) complexes may be expected to yield alternative products when reaction of the nascent $[MoOS]^{2+}$ center is possible; consequently, crystallographic characterization of reputed

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(7) For **3**: Complex **1** was prepared using the method developed for dithiophosphate complexes.[6b] A solution of **1** (1.00 g, 18.0 mmol) in 1,2-dichloroethane (15 mL) was treated with propylene sulfide (0.70 mL, 90 mmol) and refluxed for 1 day. The resultant dark yellow solution was eluted with dichloromethane on a silica column, and the product was collected as a yellow-orange band. Recrystallization by dropwise addition of methanol to a saturated dichloromethane solution produced red-brown crystals: yield 78%; mass spectrum m/z 624 (85) $[M]^+$; IR (KBr) ν(BH) 2550 m, ν(Mo=O) 930 s cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.94, 5.92 and 5.51 (s, 3 × 1 H, 3 × CH of $HB(Me_2pz)_3^-$), 2.77, 2.73, 2.22, and 2.10 (s, 4 × 3 H, 4 × CH_3 of $HB(Me_2pz)_3^-$), 2.39 (s, 6 H, 2 × CH_3 of $HB(Me_2pz)_3^-$), 1.58 (dd, 3 H, $J_{CH_3\text{-}P}$ = 19 Hz, $J_{CH_3\text{-}H}$ = 7 Hz, CH_3 of $S_2PPr^i_2^-$), 1.53 (dd, 3 H, $J_{CH_3\text{-}P}$ = 19 Hz, $J_{CH_3\text{-}H}$ = 7 Hz, CH_3 of $S_2PPr^i_2^-$), 1.22 (dd, 6 H, $J_{CH_3\text{-}P}$ = 19 Hz, $J_{CH_3\text{-}H}$ = 7 Hz, 2 × CH_3 of $S_2PPr^i_2^-$); electronic spectrum (CH_2Cl_2) λ nm (ϵ M^{-1} cm^{-1}) 530 (sh), 450 (3320), 350 (sh), 335 (5740). Anal. Calcd for $C_{21}H_{36}BMoN_6OPS_3$: C, 40.52; H, 5.83; N, 13.50; S, 15.45. Found: C, 40.30; H, 5.88; N, 13.38; S, 15.26.

(8) Crystallographic data: **3**, $C_{21}H_{36}BMoN_6OPS_3$, fw 622.5, monoclinic space group $P2_1/n$ with a = 12.601 (1) Å, b = 10.899 (1) Å, c = 20.595 (3) Å, β = 90.09 (1)°, V = 2828.5 Å^3, and D_c = 1.462 g cm^{-3} for Z = 4. The structure was solved using the Patterson method and refined by a full-matrix least-squares procedure, using 2390 data, to a conventional R value of 0.041 (R_w = 0.041).

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(19) Assuming double and single sulfur–sulfur bond distances of 1.89 (for gaseous S_2) and 2.05 Å, respectively, the equation $D(n) = D(1) - 0.66 \log n$, where $D(n)$ and $D(1)$ are the bond distances for bonds of order n and 1, respectively, may be derived. This gives an estimated bond order of 1/3 for the S(1)–S(3) bond in **3**. A bond order close to 2 can be similarly derived for the Mo–S(1) bond. See: Pauling, L. *The Nature of the Chemical Bond*; 3rd ed.; Cornell: Ithaca, NY: 1960; p 239.

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$[MoOS]^{2+}$ complexes is highly desirable.

Stabilization of enzymatic $[MoOS]^{2+}$ centers through an active site interaction, possibly with cysteine sulfur or molybdopterin, provides an attractive reconciliation of the extreme reactivity of such groups and their presence in nature. A potential interaction between the $[MoOS]^{2+}$ center and the dithiolene moiety of Mo–co is reflected in recently reported ene-1-perthiolate-2-thiolate-molybdenum(IV) complexes.[15b] We have demonstrated that the stabilization of a $[MoOS]^{2+}$ fragment by a sulfur–sulfur interaction only slightly perturbs the Mo=S bond; it is especially significant that the Mo–S(1) distance in **3** falls within the range of Mo=S distances found in molybdoenzymes and that this range, in turn, does not extend into that established crystallographically for *cis*-oxothio- or monothio-molybdenum complexes.[10,21] Given an O=Mo=S···X fragment in the active site, it would be possible to account for other enzyme behavior by postulating the severing of the S···X interaction upon reduction or initiation of catalysis (through population of Mo=S π^* to produce a nucleophilic S center). Finally, **3** reacts quantitatively with cyanide to produce **1** and SCN^- via a short-lived intermediate; in the presence of water and oxygen this reaction yields **2** in a process which mimics the deactivation of xanthine oxidase upon cyanolysis.[22]

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Supplementary Material Available: Tables of positional parameters, anisotropic thermal parameters, bond distances, and bond angles for **3** (3 pages); tables of observed and calculated structure factors for **3** (7 pages). Ordering information is given on any current masthead page.

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Template-Directed Synthesis: Use of a Reversible Reaction

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DNA replication is fundamental to the storage, transfer, and enactment of the genetic information which defines living organisms. Template-directed reactions which model DNA replication have received a great deal of attention[1-5] and have generally involved the irreversible coupling of activated constituents to form complementary products. In an effort to better define essential features of the DNA polymerization reaction, we have developed a template-directed reaction in which the irreversible coupling step is preceded by an equilibrium between the transiently coupled and uncoupled substrates.[6] This equilibrium allows the thermodynamics of substrate–template association to direct product formation.

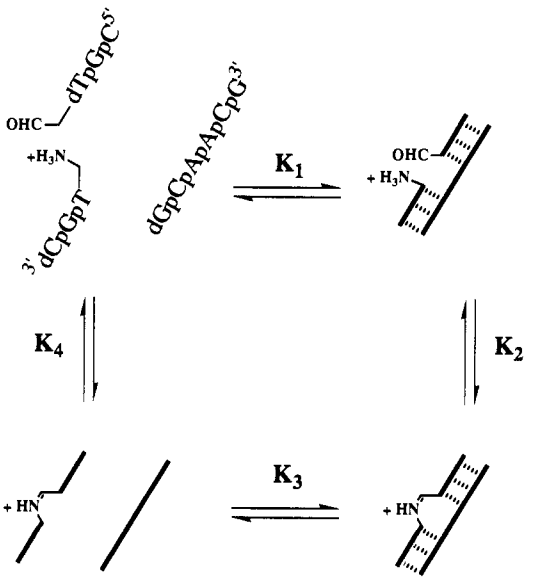
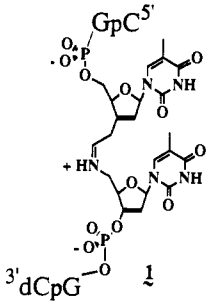


Figure 1. Thermodynamic cycle.

3′-Allyl-3′-deoxythymidine[8] was incorporated through solution-phase synthesis[9] at the 3′-terminus of a DNA trimer and 5′-amino-5′-deoxythymidine[10,11] via solid-phase synthesis[12] at the 5′-end of a separate trimer. The aldehyde was unmasked by oxidation of the allyl group with OsO_4 and $NaIO_4$.[13] The trimers were synthesized and allowed to equilibrate[7] with their imine hexamer product, **1**, under aqueous conditions, both in the absence and presence of the complementary hexamer template. The



1

reactants, template, and product can be assigned to a thermodynamic cycle (Figure 1) where the DNA association equilibria were estimated from literature data for the corresponding all-phosphate-linked oligomers:[14] $K_1 = 0.8$ (DNA ternary complex);[14,15] $K_3 = 5 \times 10^5$ (DNA duplex); $K_4 = 10^{-4}$ (imine con-

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(14) These calculations are detailed in the supplementary material.

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