Molybdenum−Pterin Chemistry. 1. The Five-Electron Oxidation of an Oxo Molybdenum Dithiolate Complex of a Reduced Pterin

Heather Layton Kaufmann,[†] Louise Liable-Sands,[‡] Arnold L. Rheingold,[‡] and Sharon J. Nieter Burgmayer*,[†]

Department of Chemistry, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010 and Department of Chemistry, University of Delaware, Newark, Delaware 19716

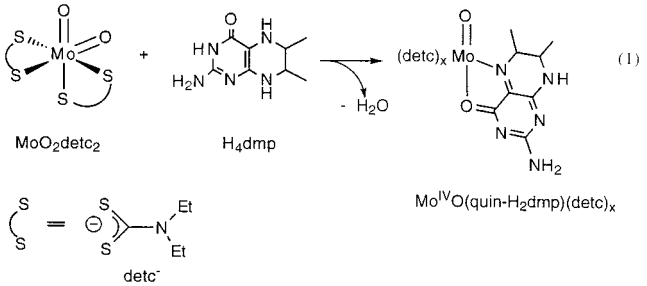
Received July 27, 1998

The synthesis and structure of a new molybdenum complex coordinated by a reduced pterin is reported. [MoOCl(detc)(H_3dmp)]Cl (**1**) (where detc is diethyldithiocarbamate and H_3dmp is 6,7-dimethyl-6,7,8-trihydropterin) is prepared from $MoOCl_2(detc)_2$ and H_4dmp (6,7-dimethyl-5,6,7,8-tetrahydropterin). The X-ray structure determination of [MoOCl(detc)(H_3dmp)]Cl·MeOH reveals an octahedral complex where the reduced pterin ligand coordinates through the carbonyl oxygen and pyrazine ring nitrogen atoms. An extensive hydrogen bonding network in the crystal lattice connects adjacent complexes, the chloride counterion, and the molecule of methanol. This hydrogen bonding persists in solution where it is identified by characteristic absorptions in the electronic spectrum. Dimethyl sulfoxide (DMSO) oxidizes [MoOCl(detc)(H_3dmp)]Cl, producing 1 equiv of dimethylpterin and $^1/_2$ equiv of oxidized dithiocarbamate, tetraethylthiuramdisulfide (TETDS), a reaction that constitutes a net five-electron oxidation of the molybdenum complex **1**. Pterin oxidation is also observed for **1** in dimethylformamide (DMF) solution where it is believed to result from intermolecular electron transfer mediated by the hydrogen-bonding network.

Introduction

In 1989 we reported the reaction of dioxomolybdenum(VI) diethyldithiocarbamate (MoO_2detc_2) with 6,7-dimethyl-5,6,7,8-tetrahydropterin (H_4dmp).[1] The motivation for this study originated in Rajagopalan's proposed structure (Figure 1) for the molybdenum cofactor.[2] The molybdenum cofactor is isolated from over three dozen enzyme sources which catalyze a variety of oxygen atom transfer reactions crucial to proper carbon, nitrogen, and sulfur metabolism. This growing class of metalloenzymes enjoys a broad distribution in nature as evidenced by their isolation from bacteria, fungi, birds, plants, and mammals.[3] The term "molybdenum cofactor" is now recognized as an ambiguous term since there does not exist just one specific structure but rather a group of related active site structures.[4]

The juxtaposition of the high oxidation state of a molybdenum(VI) center with a reduced tetrahydropterin in the proposed structure of Figure 1 prompted our investigation of the reaction in eq 1. Here MoO_2detc_2 brings the characteristics



(1)

of a sulfur-coordinated $Mo^{VI}O_2$ core and the H_4dmp provides the reducing capacity typical of tetrahydropterins. The purple product formed in eq 1 defied all isolation attempts, but its spectroscopic characterization in situ suggested the formulation MoO(quinonoid-H_2dmp)$(detc)_x$ where a molybdenum(IV) coordinated a semioxidized pterin at the carbonyl oxygen and pyrazine nitrogen atoms.[1] This formulation was consistent with the notion that a two-electron redox reaction is a possible event between the dioxo-Mo^{VI} and tetrahydropterin reagents. That molybdenum(VI) could oxidize tetrahydropterin and coordinate the partially oxidized pterin product were provocative results in the absence of a definitive structure for the molybdenum cofactor.

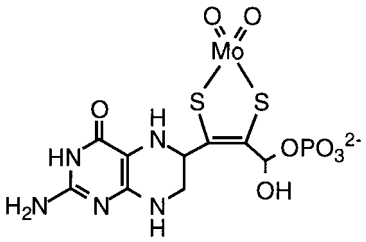


Figure 1. Structure of the dioxo-Mo(VI) form of the molybdenum cofactor as proposed by Rajagopalan in 1982.[2]

In this paper we present the identity of the product formed in eq 1 as [MoOCl(detc)(H_3dmp)]Cl (**1**) and describe its improved synthesis and isolation from an alternative preparation method. The complete characterization of **1** includes an X-ray

* To whom correspondence should be addressed.
† Bryn Mawr College.
‡ University of Delaware

(1) Burgmayer, S. J. N.; Baruch, A.; Kerr, K.; Yoon, K. *J. Am. Chem. Soc.* **1989**, *111*, 4982.
(2) (a) Johnson, J. L.; Hainline, B. E.; Rajagopalan, K. V.; Arison, B. H. *J. Biol. Chem.* **1984**, *259*, 5414. (b) Johnson, J. L.; Rajagopalan, K. V. *Proc. Natl. Acad. Sci. U.S.A.* **1982**, *79*, 6856.
(3) Hille, R. *Chem. Rev.* **1996**, *96*, 2757.
(4) Enemark, J. E.; Garner, C. D. *J. Biol. Inorg. Chem.* **1997**, *2*, 817.

10.1021/ic980881z CCC: $18.00
Published on Web 05/07/1999

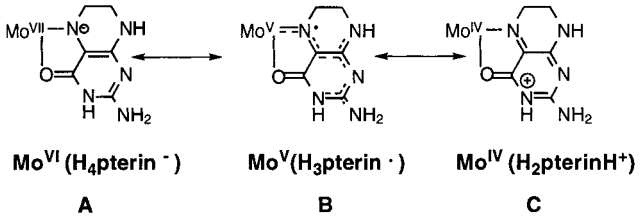


Figure 2. Resonance structure descriptions of reduced pterin coordinated to molybdenum.

crystal structure which reveals intermolecular hydrogen bonding that is responsible for unusual reactivity in common organic solvents.

Variations of eq 1 have been studied for nearly a decade in our group, and some of these results were recently reported.[5] A number of different MoO_2L reagents have been observed to react with a variety of tetrahydropterins, and all reaction systems have produced red-purple complexes that are spectroscopically similar to the product of eq 1.[6] Through these investigations it became apparent that the electronic distribution implied by the Mo(IV)-H_2pterin oxidation state description (eq 1) was not correct and that a full two-electron transfer does not necessarily occur when a tetrahydropterin reacts with and binds to Mo(VI). This view was reached by exploring the chemical reactivity of the molybdenum-reduced pterin complexes combined with theoretical calculations to determine the charge on molybdenum. The chemical behavior of these complexes spans the range between the limiting structures of molybdenum(IV) coordinated to a protonated dihydropterin, Mo(IV)(H_2pterinH^+), and molybdenum(VI) coordinated to a deprotonated tetrahydropterin, Mo(VI)(H_4pterin$^-$) (Figure 2). We have concluded that the best electronic description of these complexes refers to a delocalized system (structure **B** in Figure 2) rather than alternate structures **A** and **C** which fail to effectively account for all the observed reaction chemistry of these compounds. This interpretation is verified by recent X-ray photoelectron studies on a series of molybdenum−pterin complexes.[7] Since in all three of the pertinent resonance structures **A**, **B**, and **C** the pterin effectively retains three hydrogens, we now prefer to refer to the coordinated pterin in these compounds as *trihydropterin* (H_3pterin) or simply *reduced pterin* rather than employ the misleading labels tetrahydropterin or dihydropterin.

During our studies directed at understanding the appropriate charge distribution in the molybdenum-reduced pterin complexes, the reactivity with DMSO was explored. It was discovered that mono-oxo molybdenum dithiocarbamate complexes of reduced pterin have the ability to reduce DMSO, thus demonstrating the oxygen atom transfer reaction characteristic of molybdenum enzymes and many Mo(IV) complexes.[8] The details of DMSO oxidation of compound **1** are presented herein where, remarkably, DMSO oxidizes not only the molybdenum to a dioxo-Mo(VI) center but additionally causes formation of fully oxidized pterin and the oxidized disulfide form of dithiocarbamate in a five-electron redox reaction.

Experimental Section

Materials. All chemicals were purchased from Aldrich unless otherwise noted and used without further purification except as noted below. The molybdenum reagents, MoO_2detc_2 and $MoOCl_2detc_2$,[9] and the tetrahydropterin reagents H_4dmp·2HCl (6,7-dimethyl-5,6,7,8-tetrahydropterin dihydrochloride)[10] and H_4hmp·2HCl (6-hydroxymethyl-5,6,7,8-tetrahydropterin dihydrochloride)[11] were synthesized according to published preparations. Solvents were dried over 4 Å molecular sieves except methanol, which was dried over 3 Å molecular sieves, stored under N_2, and used without further purification. All molybdenum reactions were performed in standard laboratory glassware under a nitrogen atmosphere in a Vacuum Atmospheres drybox. NMR spectra were obtained using an IBM 300 MHz FT-NMR, and chemical shifts are reported in parts per million referenced to internal TMS or solvent. Infrared spectra of samples of KBr disks were recorded on a Perkin-Elmer FT-IR Model 2000 instrument and are referenced to the 1601.4 cm^{-1} absorption of polystyrene. Electronic spectra were recorded using a Hewlett-Packard 8452A spectrophotometer. Solution conductivities were measured using a Barnstead PM-70CB conductivity bridge equipped with a Yellow Springs Instruments 3403 dip cell. Microanalyses were performed by Robertson Microanalytical Labs, Madison, NJ.

[MoOCl(detc)(H_3dmp)]Cl (1). A white slurry of H_4dmp·2HCl (0.268 g, 1.0 mmol) in methanol (24 mL) was slowly added dropwise to a stirred yellow solution of $MoOCl_2detc_2$ (0.408 g, 1.0 mmol) in methylene chloride (26 mL). A color progression from yellow to orange to red/orange to deep red occurred over the next 24 h. A small amount of unreacted and precipitated H_4dmp·2HCl was removed by filtration, and the solution was concentrated to one-third the original volume. Within 7 days, a dark purple crystalline solid formed. This solid was isolated and washed with ether to give **1** (0.28 g, 50% yield, based on pterin). Crystals for X-ray determination were obtained by placing aliquots of the filtered reaction solution into 20 mL scintillation vials. Crystals suitable for X-ray diffraction grew over 9 days. Anal. Calcd for $MoO_3C_{14}H_{27}N_6S_2Cl_2$ [MoOCl(detc)(H_3dmp)]Cl·MeOH: C, 30.11; H, 4.87; N, 15.05; S, 11.48; Cl, 12.70. Found: C, 30.07; H, 4.69; N, 14.93; S, 11.73; Cl, 12.42.

[MoOCl(detc)(H_3hmp)]Cl (2). A tan solution of H_4hmp·2HCl (0.136 g, 0.5 mmol) in methanol (10 mL) was added slowly dropwise to a stirred yellow solution of $MoOCl_2detc_2$ (0.204 g, 0.5 mmol) in methylene chloride (15 mL). The solution changed color from yellow to red within 2 h and stirred overnight. After 2 days a dark purple crystalline solid formed, was isolated, and was washed with ether. All properties (UV/vis, IR, NMR) agree with those previously reported.[5]

DMSO Oxidation of [MoOCl(detc)(H_3dmp)]Cl. In the drybox, **1** (16 mg) was dissolved in 0.75 mL of d_6-dimethyl sulfoxide to form a dark purple solution which was transferred to an NMR tube. After sitting overnight in the box, the solution color turned orange and a pale precipitate (6,7-dimethylpterin) formed on the bottom of the tube. ^{1}H and ^{13}C NMR spectra were obtained revealing the presence of DMS in the sample. After 19 days, a stoichiometric amount of H_4dmp (7.7 mg) was added to the NMR tube. The solution regained its original purple/red color. The reaction was monitored by ^{1}H NMR at intervals of 30 min, 4 h, and 1 day.

Quantitation of DMS. In the drybox, **1** (0.020 g, 0.0358 mmol) was dissolved in DMSO (0.5 mL) in a vial. Benzene (3.2 μL) was added to the dark purple solution in a 1:1 stoichiometry with **1** to serve as an internal standard. The vial was capped with a septum and allowed to sit for about 3 weeks until the solution color was yellow and pale solid had formed on the bottom of the vial, indicating that the reaction was complete. An aliquot of the reaction solution (3 μL) was placed in a NMR tube containing d_4-methanol and a spectrum was taken. The signals due to benzene and DMS were integrated to determine the stoichiometry of DMS in the reaction. A control sample having a 1:1 benzene/DMS molar ratio was used to obtain the relative integration

(5) Burgmayer, S. J. N.; Arkin, M. R.; Bostick, L.; Dempster, S.; Everett, K. M.; Layton, H. L.; Paul, K. E.; Rogge, C.; Rheingold, A. L. *J. Am. Chem. Soc.* **1995**, *117*, 5812.
(6) (a) Fischer, B.; Schmalle, H.; Dubler, E.; Schäfer, A.; Viscontini, M. *Inorg. Chem.* **1995**, *34*, 5726. (b) Fischer, B.; Strähle, J.; Viscontini, M. *Helv. Chim. Acta* **1991**, *74*, 1544. (c) Fischer, B.; Schmalle, H.; Baumgartner, M.; Viscontini, M. *Helv. Chim. Acta* **1997**, *80*, 103.
(7) Burgmayer, S. J. N.; Kaufmann, H. L.; Fischer, B.; Fortunato, G.; Hug, P. *Inorg. Chem.* **1999**, *38*, 2607.
(8) Holm, R. H. *Coord. Chem. Rev.* **1990**, *100*, 183.
(9) Young, C., et al. *J. Chem. Educ.* **1995**, *72*, 751.
(10) Mager, H. I. X.; Addink, R.; Berendo, W. *Recl. Trav. Chem.* **1967**, *86*, 833.
(11) Baugh, C. M.; Shaw, E. *J. Org. Chem.* **1964**, *29*, 3610. The procedure in ref 10 was followed for the reduction of hmp to H_4hmp with the substitution of methanol as solvent.

Table 1. Crystallographic Data for [MoOCl(detc)(H_3Dmp)][Cl]·CH_3OH (**1**)

formula	$C_{14}H_{26}Cl_2MoN_6O_3S_2$
formular weight	557.4
space group	$P2_1/c$ (#14)
a, Å	13.253(8)
b, Å	14.130(3)
c, Å	12.689(8)
β, deg	93.66(5)
V, Å^3	2371(2)
Z	4
ρ(calcd), g cm^{-3}	1.561
μ(Mo Kα), cm^{-1}	9.80
temp, K	246
radiation	Mo Kα ($\lambda = 0.71073$ Å)
$R(F)$,[a] %	4.58
$R(wF^2)$,[a] %	5.53

[a] Quantity minimized $= \sum w\Delta^2$; $R = \sum\Delta/\sum(F_o)$; $R(w) = \sum w^{1/2}\Delta/\sum(F_o w^{1/2})$, $\Delta = (F_o - F_\chi)$.

response of benzene vs DMS. Three trials yielded DMS:benzene ratios of 2.4, 2.3, and 2.3 for an average of 2.33 equiv of DMS produced per **1**.

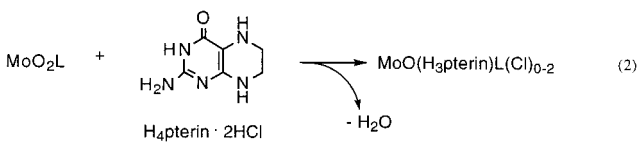
UV/vis Study of Addition of Acid and Base to [MoOCl(detc)(H_3dmp)]Cl. A red solution of **1** in acetonitrile was prepared in a cuvette and capped with a septum. After measurement of the initial spectrum, 2 μL of NEt_3 was added to the cuvette, causing a color change of the solution to purple, and the spectrum was recorded. Concentrated HCl was added in microliter quantities until the solution color returned to its original red color and a spectrum was recorded. The experiment was repeated for methanol. For a solution of **1** in DMF, the acid was added first followed by the base.

^{1}H NMR of [MoOCl(detc)(H_3dmp)]Cl and 8-Hydroxyquinoline. In the drybox, a colorless solution of 8-hydroxyquinoline (0.0018 g, 0.0125 mmol) in d_4-methanol was added to a dark red solution of **1** (0.0070 g, 0.0125 mmol) dissolved in d_4-methanol resulting in a purple solution. This solution was transferred to an NMR tube and spectra were taken after 0.5 h, 1 day, and 2 days.

X-ray Structure Determination of [MoOCl(detc)(H_3dmp)]Cl (1). Preliminary photographic data indicated a monoclinic crystal system, and the systematic absences in the diffraction data are uniquely consistent with the reported space group. The structure was solved using direct methods, completed by subsequent difference Fourier syntheses and refined by full-matrix least-squares procedures. Semiempirical absorption corrections were applied. A solvent molecule of methanol was located in the asymmetric unit. Carbon atoms C(1), C(2), and C(3) are disordered over two positions with an occupancy distribution of 60/40 and were refined isotropically. All other non-hydrogen atoms were refined with anisotropic displacement coefficients. Hydrogen atoms were treated as idealized contributions, except for those on the disordered carbon atoms, which were ignored. All software and sources of the scattering factors are contained in the SHELXTL (4.2) program library (G. Sheldrick, Siemens XRD, Madison, WI).[12] Details of data collection and refinement are given in Table 1.

Results

Syntheses. The synthesis of reduced pterin complexes of molybdenum readily occurs through reaction of a dioxo molybdenum(VI) reagent with a fully reduced pterin (eq 2). The



(2)

presence of hydrochloric acid associated with the pterin

(12) Sheldrick, G. M. *SHELXL-93: Program for the Refinement of Crystal Structures*; University of Göttingen: Germany, 1993.

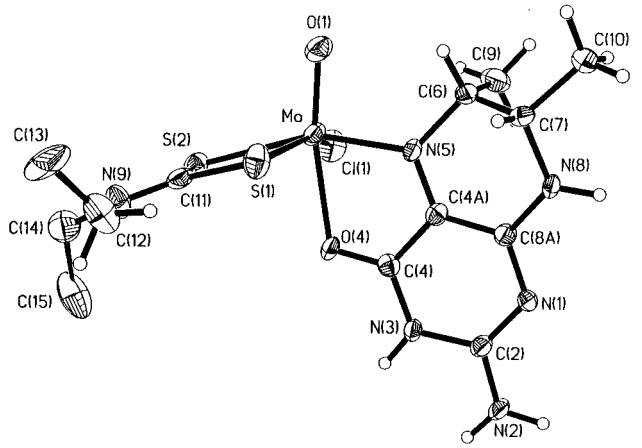
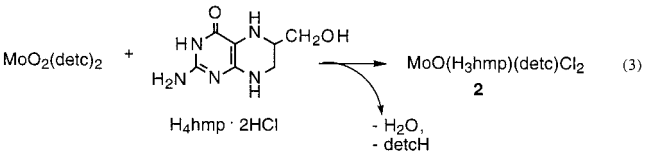


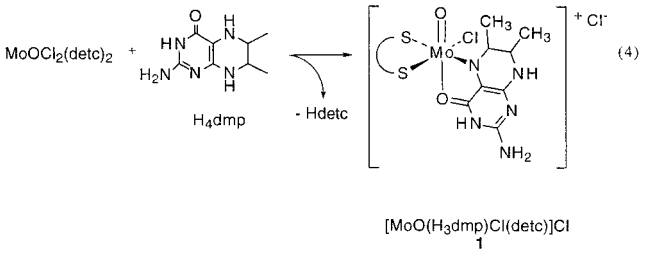
Figure 3. ORTEP drawing of [MoOCl(detc)(H_3dmp)]Cl·MeOH (**1**) with the thermal ellipsoids drawn at 30% probability.

facilitates the reaction by protonating an oxo group on the molybdenum reagent prior to its removal as water. The first reaction studied of this type, shown earlier in eq 1, used MoO_2(detc)$_2$ and H_4dmp (5,6,7,8-tetrahydro-6,7-dimethylpterin) (eq 1).[1] Although the product obtained using H_4dmp could not be cleanly isolated, use of a different tetrahydropterin, 6-hydroxymethyl-5,6,7,8-tetrahydropterin (H_4hmp), facilitated the isolation and characterization of a dark red product having the elemental formula $MoOCl_2$(detc)(H_3hmp) (**2**) (eq 3).[5] $MoOCl_2$-



(3)

(detc)(H_3hmp) was spectroscopically identical with the product of eq 1. Solution studies revealed that one chloride of $MoOCl_2$(detc)(H_3hmp) was labile and easily replaced by solvent. This solution behavior suggested that isolation of **1** would be enhanced by high chloride ion concentration. With this idea in mind, a new route was developed using starting reagent $MoOCl_2$-$detc_2$ which contained one oxo group and could supply additional chloride ions into the solution (eq 4).



(4)

The result is a cleaner, faster synthesis of [MoOCl(detc)(H_3dmp)]Cl (**1**). The yield of **1** from eq 4 is limited by the insolubility of H_4dmp·2HCl in the CH_2Cl_2/MeOH solvent mixture. When 5,6,7,8-tetrahydro-6-hydroxymethylpterin is used in eq 4, the complex [MoOCl(detc)(H_3hmp)]Cl is also cleanly isolated by this method. Using this synthetic route, diffraction quality crystals of the complex [MoOCl(detc)(H_3dmp)]Cl (**1**) were grown directly from the reaction mixture.

Crystal Structure of [MoOCl(detc)(H_3dmp)]Cl·MeOH (1). The structure of **1** was proved by single-crystal diffraction analysis. An ORTEP drawing of one molecule is given in Figure 3 while Figure 4 illustrates intermolecular hydrogen bonding.

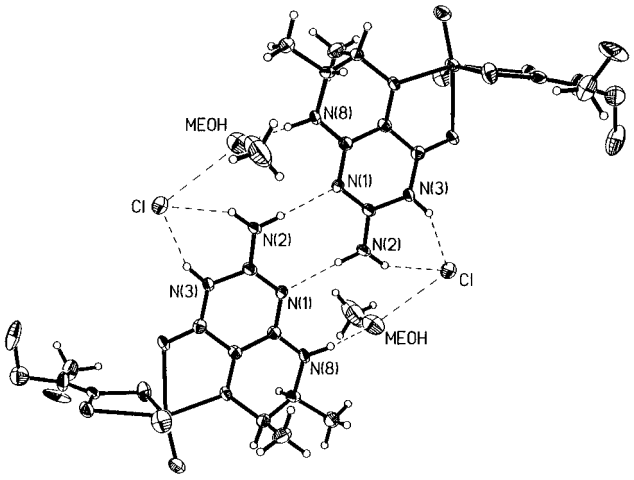


Figure 4. ORTEP drawing illustrating the hydrogen bonding interactions between two molecular units of [MoOCl(detc)(H_3dmp)]Cl·MeOH (**1**).

Table 2. Selected Bond Lengths and Angles for [MoOCl(detc)(H_3Dmp)]Cl·MeOH

	Bond Lengths, Å		
Mo−Cl1	2.360 (3)	N(1)−C(2)	1.331 (12)
Mo−S1	2.449 (3)	N(1)−C(8a)	1.349 (11)
Mo−S2	2.460 (3)	N(8)−C(8a)	1.334 (11)
Mo−O4	2.290 (6)	N8−C7	1.457 (12)
Mo−O1	1.654 (7)	N5−C4a	1.329 (11)
Mo−N5	2.027 (7)	N5−C6	1.492 (11)
S(1)−C(11)	1.731 (10)	C13−C12	1.392 (38)
S(2)−C(11)	1.731 (10)	C(15)−C(14)	1.412 (36)
O(4)−C(4)	1.245 (11)	C(4)−C(4a)	1.432 (13)
N(9)−C(12)	1.541 (29)	C(8a)−C(4a)	1.404 (13)
N(9)−C(14)	1.486 (14)	C(6)−C(9)	1.499 (13)
N(9)−C(11)	1.297 (13)	C(6)−C(7)	1.532 (13)
N(3)−C(4)	1.360 (12)	C(7)−C(10)	1.510 (14)
N(3)−C(2)	1.384 (11)	C(16)−O(5)	1.507 (18)
N(2)−C(2)	1.319 (12)		
	H-Bonding Contacts, Å		
N(1)−N(2)	2.948	N(8)−O(MeOH)	2.921
Cl−N(3)	3.117	Cl −N(2)	3.200
Cl−O(MeOH)	3.087		
	Bond Angles, deg		
Cl(1)−Mo−S(1)	155.4(1)	N(9)−C(12)−C(13)	113.2(20)
Cl(1)−Mo−S(2)	87.4(1)	N(9)−C(14)−C(15)	115.5(15)
S(1)−Mo−S(2)	71.9(1)	S(1)−C(11)−S(2)	112.8(5)
Cl(1)−Mo−O(1)	99.0(2)	S(1)−C(11)−N(9)	123.2(7)
S(1)−Mo−O(1)	99.8(2)	S(2)−C(11)−N(9)	124.0(8)
S(2)−Mo−O(1)	107.6(2)	O(4)−C(4)−N(3)	123.5(8)
O(4)−Mo−O(1)	169.0(3)	O(4)−C(4)−C(4a)	119.5(8)
Cl(1)−Mo−N(5)	98.8(2)	N(3)−C(4)−C(4a)	117.0(8)
S(1)−Mo−N(5)	95.0(2)	N(3)−C(2)−N(2)	115.1(8)
S(2)−Mo−N(5)	155.2(2)	N(3)−C(2)−N(1)	124.0(8)
O(4)−Mo−N(5)	74.1(2)	N(2)−C(2)−N(1)	120.9(8)
O(1)−Mo−N(5)	95.1(3)	N(1)−C(8a)−N(8)	119.3(8)
Mo−S(1)−C(11)	87.8(3)	N(1)−C(8a)−C(4a)	122.0(8)
Mo−S(2)−C(11)	87.5(3)	N(8)−C(8a)−C(4a)	118.7(8)
Mo−O(4)−C(4)	111.5(6)	N(5)−C(4a)−C(4)	114.8(8)
C(12)−N(9)−C(14)	118.6(12)	N(5)−C(4a)−C(8a)	126.2(8)
C(12)−N(9)−C11)	118.0(12)	C(4)−C(4a)−C(8a)	118.9(8)
C(14)−N(9)−C(11)	122.8(9)	N(5)−C(6)−C(9)	107.5(7)
C(4)−N(3)−C(2)	120.2(7)	N(5)−C(6)−C(7)	109.3(7)
C(2)−N(1)−C(8a)	117.5(7)	C(9)−C(6)−C(7)	115.1(8)
C(8a)−N(8)−C(7)	118.0(7)	N(8)−C(7)−C(6)	110.3(8)
Mo−N(5)−C(4a)	120.0(6)	N(8)−C(7)−C(10)	109.3(8)
Mo−N(5)−C(6)	125.4(5)	C(6)−C(7)−C(10)	113.4(8)
C(4a)−N(5)−C(6)	114.3(7)		

Selected intramolecular and intermolecular bond distances and angles are listed in Table 2. The asymmetric unit consists of one unique formula unit of **1** and one molecule of methanol from the crystallization solvent. The geometry around the molybdenum is distorted octahedral, a result of the small bite angles of the diethyldithiocarbamate and pterin chelates (72° and 74°, respectively). The pterin binds to the molybdenum through its N5 and O4 atoms. The short Mo−N5 bond (2.029 Å) implies partial double bond character, a feature also observed in every other reduced pterin molybdenum complex.[5,6] The carbon atoms C6 and C7 in the pterin ligand have tetrahedral geometry indicating the reduced nature of the coordinated pterin.

Table 3. Physical Properties of [MoOCl(detc)(H_3dmp)]Cl (**1**)

	IR (cm^{-1})	
ν(Mo═O)	ν(CO,CN)	ν(Mo−S)
977	1490, 1534, 1579, 1629, 1677	379
	UV/Vis	
	λ, nm (ϵ, L mol^{-1} cm^{-1})	
methanol (red)	286(sh), 500(19 000)	
methanol (purple)	506, 580	
DMF	264, 286(sh), 354(sh), 522(8200), 584(7570)	
DMSO	268, 354(sh), 528(14 400), 570(12 100)	

	^{1}H NMR (δ, ppm)			
	H6, dq	H7, dq	Me6, Me7, d	NH, s
d_4-methanol	5.7	4.32	1.58	
d_7-DMR	5.72, 5.68	4.5, 4.37	1.64, 1.58, 1.45	
d_6-DMSO	5.55	4.3, 4.2	1.5, 1.44	9.3, 8.4, 7.67 (br)

	Solution Conductivity	
	Λ, ohm^{-1} M^{-1}	electrolyte type
methanol	140	between 1:1 and 1:2
DMF	35	<1:1
DMSO	29	1:1

The bond lengths within the pterin are similar to those reported for other reduced pterin complexes of molybdenum.[5,6] The addition of sulfur atoms in the molybdenum coordination sphere does not appear to affect the structural parameters of the coordinated pterin. Turning attention to the Mo−S bond lengths associated with the dithiocarbamate ligand, the Mo−S2 bond positioned trans to the pterin N5 is slightly longer than the related Mo−S1 bond that is trans to Cl1. This is a typical result of Mo−L bond lengthening observed when Mo−L is trans to a Mo═O unit. Hence the increased length of Mo−S2 confirms the partial multiple bond order in the Mo−N5 unit.

Several interesting hydrogen bonding interactions are observed in the crystal lattice. Most surprising was an hydrogen bonding interaction between the pterins on two different molecules of **1** in the region of atoms N1, N2, and N8 (Figure 4). Reinforcing this interaction is hydrogen bonding involving both the chloride counterion and the molecule of methanol in the unit cell where methanol bridges the hydrogen on N8 of one pterin to the chloride and the amine proton on N2 of the second pterin. The important hydrogen bonding distances are included in Table 2. The formation of a dimeric species through hydrogen bonding interactions is believed to play an important role in the solution reactivity of **1**.

Spectroscopic Characterization of the Solution Behavior of [MoOCl(detc)(H_3dmp)]Cl·MeOH (1). The spectroscopic properties of compound **1** (Table 3) resemble those of other molybdenum-reduced pterin compounds previously reported.[5,6] In the infrared spectrum a strong absorption due to νMo═O occurs at 977 cm^{-1}. This value is consistent with the range of frequencies observed for the Mo═O unit in other mono-oxo molybdenum−pterin complexes.

Consistent with the documented behavior of other molybdenum−pterin complexes, [MoOCl(detc)(H_3dmp)]Cl is a reactive

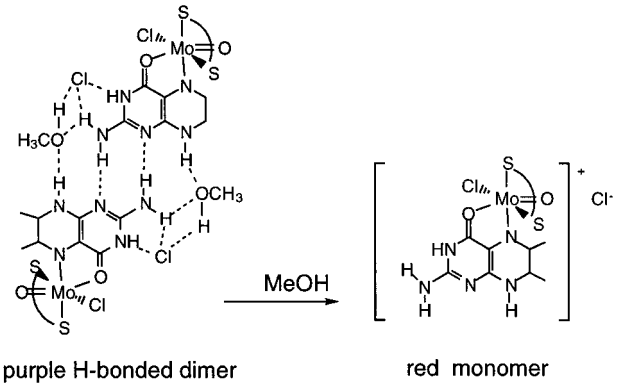


Figure 5. Dissociation of hydrogen-bonded dimers of **1** in methanol. Dashed lines represent the hydrogen-bonded network.

species in solution.[5] Four reactivity types are observed: (1) disruption of hydrogen-bonded dimers; (2) solvent substitution of chloride; (3) tetrahydropterin oxidation to fully oxidized pterin; (4) oxygen atom transfer. The evidence for each of these will be described in turn.

Disruption of Hydrogen Bonds. The complicated solution behavior for **1** in several solvents can be monitored by electronic spectroscopy which reveals substantial solvent interactions. For example, dissolution of **1** in methanol immediately forms a purple solution which changes to a dark red color within seconds. We interpret this rapid solvation reaction as the disruption of hydrogen bonds between two molecules of **1** as illustrated in Figure 5. This dimer is identical to the hydrogen-bonded structure observed for the single-crystal structure of **1** as described in the previous section. The loss of extensive hydrogen bonding transforms the dimer into solvated red-colored monomers. In methanol the transient purple dimer is characterized by two overlapping absorption bands at 506 and 580 nm. As the dimer dissociates into solvated monomers, the solution becomes dark red and electronic spectroscopy reveals that the two absorption bands of the purple species coalesce to produce only one absorption at 500 nm of approximately twice the intensity (Table 3). The assignment of the ~500 nm absorption to a monomeric species is based on the spectral signature of similar compounds identified in earlier work.[5] Dissolution of **1** in acetonitrile gives different results. **1** dissolved in acetonitrile instantaneously produces a red solution. However, at suffiently high concentrations (>0.03 M) a purple solid precipitates which has been characterized by ^{1}H NMR and IR. Its NMR spectrum in d_4-methanol displays the usual resonances that characterize **1** with the notable absence of a methyl resonance at 3.3 ppm assigned to the hydrogen-bonded methanol in the lattice. The purple color of the precipitate suggests a dimeric hydrogen-bonded species. The absence of any resonance due to acetonitrile in the ^{1}H NMR spectrum indicates that acetonitrile is not being incorporated into this altered structure of **1**. We conclude that the acetonitrile favors monomers in solution upon initial dissolution of **1** but that the low solubility of a diffrent hydrogen-bonded dimeric species in acetonitrile causes its eventual precipitation. This new dimeric species has a ν(Mo═O) shifted from 972 (as isolated from methanol) to 965 cm^{-1} (when isolated from acetonitrile), indicating a new electronic environment where less electron density is transferred from the Mo═O bond to Mo. The behavior of **1** in dimethylformamide or dimethyl sulfoxide solutions is very different from that in methanol and acetonitrile solutions. **1** appears purple in DMF or DMSO until subsequent complex degradation occurs (described below). The corresponding UV/vis spectrum reveals two bands at 522 and 582 nm. No red solutions nor absorptions characteristic of the solvated monomers are observed in these solvents. The resistance of the hydrogen-bonded dimer in DMF toward dissociation is verified by low conductivity values which are in the range below that expected for a 1:1 salt (Table 3).

A reversible disruption of hydrogen bonds can also be induced by changing the acidic or basic conditions of solutions of **1**. We have previously described such behavior for molybdenum-reduced pterin complexes where a color change from red to purple was associated with bimolecular hydrogen bonding.[5] Similar reactivity was observed for **1**. The dark purple color characteristic of hydrogen-bonded dimeric **1** in DMF and DMSO can be changed to red by addition of HCl. UV/vis spectra display a shift from two bands at 524 and 586 nm to a single asymmetric band at 502 nm. Subsequent addition of NEt_3 results in the reappearance of the purple species demonstrating the reversibility of the reaction. The decreased intensity of the prominent absorption band is attributed to decomposition of the complex in solution accelerated by the pH changes. **1** exhibits the same reactivity in acetonitrile where the addition of NEt_3 causes the appearance of a purple color corresponding to a shift of the original absorption at 494 nm to two bands at 512 and 574 nm. Subsequent addition of HCl causes a reappearance of the red color (494 nm) accompanied by a marked decrease in absorbance intensity.

Chloride Substitution. Solvent substitution for coordinated chloride has been been previously documented for reduced pterin complexes of molybdenum.[5] The characteristics of this process for **1** have been observed by several spectroscopic and conductivity measurements. For example, chloride substitution is revealed when a red methanolic solution of **1** is monitored by ^{1}H NMR over 14 days. Specifically, additional signals for pterin protons H6, Me6, and Me7 appear within 24 h and an equilibrium is established between this new species and the original complex after 2 days, at which time the ratio of new complex to original is 1:2. Conductivity measurements confirm that the new species is a 2:1 electrolyte since the initial conductivity appropriate for a 1:1 salt increases after several days to the level characteristic of a 2:1 salt. This information supports formation of $[MoO(detc)(H_3dmp)(MeOH)]^{2+}$ from chloride substitution. ^{1}H NMR spectra indicate that neither the pterin nor the dithiocarbamate ligand dissociates. In more dilute samples, the methanol further substitutes for pterin and dithiocarbamate ligands in addition to chloride, thus ultimately causing degradation.

Tetrahydropterin Oxidation in DMF. Complex **1** demonstrates unexpectedly complicated reactivity in dimethylformamide. The degradation of the complex is best monitored by ^{1}H NMR. An initial spectrum of **1** displays two sets of double quartet resonances at 5.72 and 5.68 ppm (H6) and 4.5 and 4.37 ppm (H7) and two sets of doublets at 1.60 and 1.45 ppm (Me6, Me7), indicating the presence of two species in a ratio of 2:1. These two species are the hydrogen-bonded dimer (downfield resonances) and the solvent-substituted complex $[MoO(detc)(H_3dmp)(DMF)]^{2+}$ (upfield resonances). Uncoordinated H_4dmp and semioxidized pterin, 7,8-H_2dmp, are detected in the initial spectrum of **1** in d_7-DMF; fully oxidized pterin appears after 5 h. After 1 day, the solution color has changed from purple to dark red-orange and oxidized pterin has visibly precipitated out of solution. The initial set of signals attributed to the complex are no longer observed in the spectrum. After 24 h the presence of $Mo(IV)O(detc)_2$ is indicated by both the color and its characteristic diethyldithiocarbamate multiplet at 4.0 ppm. After 2 days, water is apparent in the ^{1}H NMR spectrum and a new triplet at 1.6 ppm reveals formation of tetraethylthiuramdisulfide

(TETDS). After 12 days, degradation of $MoOdetc_2$ commences. Control experiments demonstrate that $H_4dmp \cdot 2HCl$ is stable in d_7-DMF for at least 3 weeks, and $MoO(detc)_2$, which is observed to form a red/orange solution in d_7-DMF, produces less than 3% dissociated dithiocarbamate after 2 weeks. The formation of oxidized pterin (dmp) and the disulfide TETDS was unexpected, and the yield of these oxidized species was not always reproducible. The formation of TETDS appears to correlate with trace water in the solvent, since drying d_7-DMF over 4 Å molecular sieves suppresses TETDS formation.

Oxidation by DMSO. Dissolution of **1** in DMSO results in a dark purple solution which fades to yellow after 1 day, duplicating similar observations previously made for the related complex $MoO(H_3hmp)(detc)Cl_2$ in DMSO.[5] Monitoring this reaction in d_6-DMSO by ^{1}H NMR shows that free H_4dmp and H_2dmp appear after 2 h accompanied by the appearance of TETDS and free dithiocarbamate. After 1 day, the initial set of signals corresponding to **1** completely disappear. The pale orange/yellow color of the reaction solution is suggestive of dioxo-Mo(VI) species and oxidized pterin has precipitiated. After 12 days, the solution is yellow and the only solution species detected are uncoordinated dithiocarbamate, TETDS, fully oxidized pterin, and water. The signal due to water has increased steadily over the period of the experiment. These results point to an oxygen atom transfer reaction with DMSO acting as the substrate. NMR detection of DMS in the reaction mixture confirms this hypothesis.

Using the method reported by Fischer,[6a] the quantitative formation of a dioxo-Mo(VI) species was checked by addition of fresh tetrahydropterin. A stoichiometric amount of H_4dmp was added to the system after 19 days when the DMSO oxidation of **1** was determined to be complete. This caused a gradual return of the original red-purple solution color. After 4 h, coordinated pterin is clearly observed in the proton NMR spectrum. After 1 day, all of the H_4dmp has coordinated to the molybdenum, confirming the formation of a dioxo-Mo(VI) degradation product from DMSO oxidation.

Several methods were used to detect and quantify the amount of DMS produced in the reaction. A ^{13}C NMR spectrum of a sample of **1** in d_6-DMSO clearly shows the presence of d_6-DMS as a quintet at 16 ppm. Singlets at 51.5, 47.3, 13.3, and 11.2 ppm verify the presence of TETDS by ^{13}C NMR. Fischer et al. reported the quantification of DMS via a known reaction between Chloramine T and sulfides resulting in the formation of sulfilimines.[6a] Unfortunately, all attempts in our hands to quantify the amount of DMS formed using this reported method were unsuccessful.

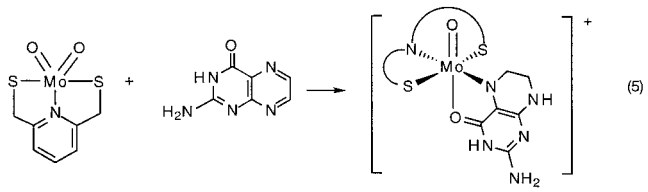
A second method was developed using benzene as an internal standard for quantifying products by integration of ^{1}H NMR spectra. An equimolar amount of benzene was added to a solution of **1** dissolved in DMSO. The ratio of the integrations obtained for benzene:DMS indicated the moles of DMS formed. The average result from three trials indicate that 2.33 mol of DMS is produced for every mole of $[MoOCl(detc)(H_3dmp)]Cl$ consumed.

Reaction with [MoOCl(detc)(H_3dmp)]Cl and Hydroxyquinoline. As previously reported for other molybdenum complexes of reduced pterins,[5] the addition of 8-hydroxyquinoline to a solution of **1** in methanol results in the dissociation of H_4dmp and the chelation of hydroxyquinoline as observed by ^{1}H NMR. After 1 h resonances corresponding to a second species are observed at 5.69(dq), 4.15(dq), and 1.49(d) in a 1:1 ratio with the original complex. After 1 day, both free tetrahydropterin and free detc are clearly observed. The resonances of hydroxyquinoline have shifted due to coordination to molybdenum.

Discussion

Our search for an example of a molybdenum complex coordinated by reduced pterin and thiolate ligands was rewarded with the unique reactivity of the complex $[MoOCl(detc)(H_3dmp)]Cl$ (**1**). This species was identified spectroscopically in our preliminary report[1] of a dioxo-molybdenum(VI) reaction with tetrahydropterin (eq 1) but eluded a clean isolation. After identifying the facile chloride substitution in an analogue of **1**, we recognized that product isolation was thwarted by formation of multiple solution species. A different synthesis was conceived that led to the successful isolation and crystallization of **1** based on use of the mono-oxo molybdenum(VI) complex $MoOCl_2(detc)_2$.

There were several motivations for pursuing the isolation and structural characterization of $[MoOCl(detc)(H_3dmp)]Cl$ (**1**). The first of these was to completely identify the product from eq 1. A second motivation was to obtain the structure of **1** since all structurally characterized molybdenum−pterin complexes to this point contained only chloride as ancillary ligands, unlike the established coordination environment for Mo in molybdoenzymes. Compound **1** would illustrate an improved model for the molybdenum cofactor incorporating sulfur atoms in the inner coordination sphere. Finally, the effect of sulfur atoms on the reactivity of the molybdenum atom was an issue deserving investigation. During our search for an improved synthesis of **1** and the study of its unusual properties, a parallel project in another lab produced a molybdenum complex, herein referred to as $MoO(L{-}S_2N)(H_3pterin)$ (**3**), coordinated by both a reduced pterin and thiolate ligands (eq 5).[6c] The relationship of **3** to our studies is discussed more fully below.



(5)

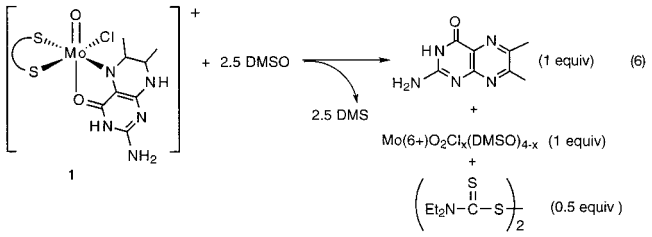
$[MoO(L\text{-}S_2N)(H_3pterin)]^+Cl^-$

3

The inclusion of thiolate ligands in both complexes **1** and **3** has a negligible effect on the structural parameters. The bond distances between Mo and the coordinated atoms of the pterin are nearly identical with those of all other Mo−reduced pterin complexes.[5,6] No significant differences can be identified within the Mo−reduced pterin unit, in part due to the relatively large esd's associated with the atom positions in the pterin ligand.

In striking contrast to the lack of structural change when sulfur atoms replace chloride in the molybdenum−pterin complexes, we find that the $[MoOCl(detc)(H_3pterin)]Cl$ complexes demonstrate a surprisingly rich reactivity, especially in the realm of redox and hydrogen bonding processes. The most fascinating of these reactions is the five-electron redox reaction with dimethyl sulfoxide.

In DMSO, **1** readily undergoes oxygen atom transfer producing a $Mo^{VI}O_2$ complex, oxidized pterin, and tetraethylthiuram-disulfide (TETDS), the oxidation product of diethyldithiocarbamate. Quantitation of the DMS indicate that 2.33 (average of three trials) mol is produced in the reaction. The net reaction (eq 6) predicts that 2.5 equiv of DMSO per molybdenum

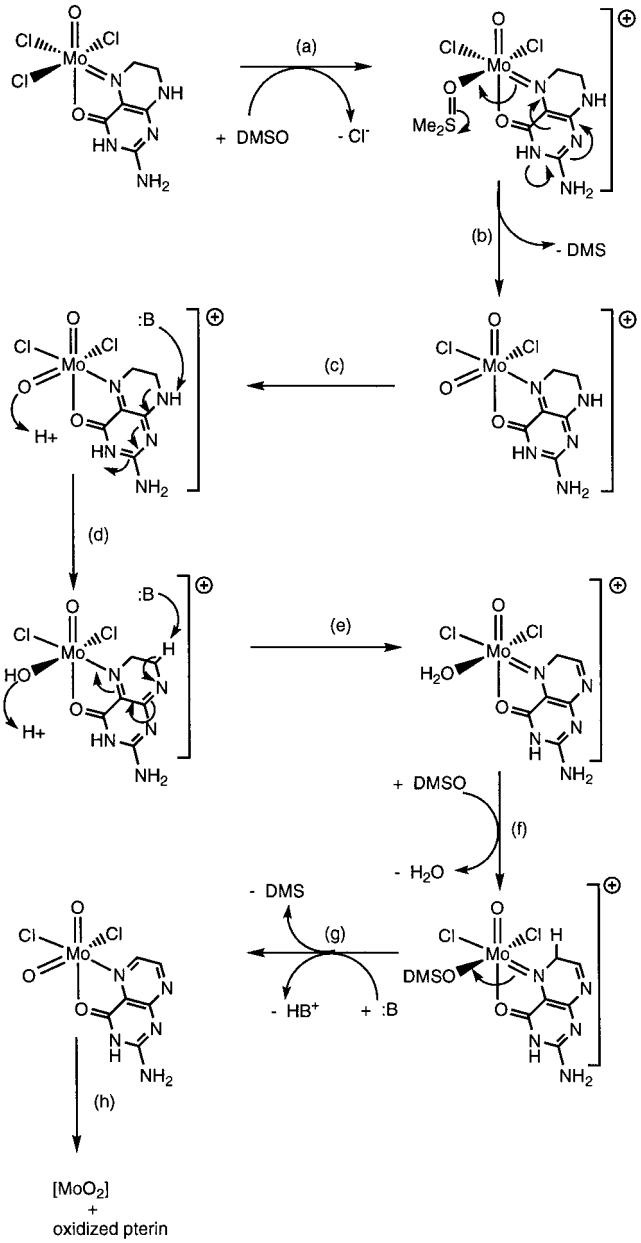


complex **1** is required for stoichiometric formation of fully oxidized pterin and a dioxo-Mo(VI) complex (4 e−), and the disulfide (1 e−).

The incorporation of sulfur atoms into the inner coordination sphere of **1** significantly modulates the molybdenum electronic environment so that oxygen atom transfer may occur. This is apparent if the behaviors of $Mo_2O_4(H_3dmp)_2Cl_2$ and $MoOCl_3(H_3dmp)$ in DMSO are compared with the reactivity of **1** in DMSO. The dimeric core in $Mo_2O_4(H_3dmp)_2Cl_2$ is stable and has no reaction with DMSO whereas the monomeric $MoOCl_3(H_3dmp)$ complex undergoes chloride substitution by DMSO to yield $[MoOCl(H_3dmp)(DMSO)]^+Cl^-$ without oxygen atom transfer.[5] It should be noted that the ability of sulfur atom donor ligands to enhance the oxygen atom transfer (OAT) ability of oxo-Mo(IV) complexes is well documented and is not a new result from this study.[8] While the incorporation of thiolate ligands into a molybdenum complex of reduced dimethylpterin is necessary to induce a redox reaction with DMSO, there exists one example of a molybdenum−pterin complex without sulfur ligands which demonstrates OAT using DMSO as substrate. $MoOCl_3(H_3pterin)$ has been reported to reduce two molecules of DMSO to DMS.[6a] The peculiar characteristics inherent in $MoOCl_3(H_3pterin)$ that result in DMSO reduction in contrast to the lack of reactivity by closely related analogues have not yet been identified. The lack of reactivity of the thiolate-coordinated molybdenum in **3** toward DMSO is evidence of the requirement of an open coordination site for DMSO coordination prior to oxygen atom transfer.[6c] While oxygen atom transfer between Mo and DMSO as demonstrated by **1** is not a novel reaction, the associated oxidation of *all* redox-active ligands coordinated to the molybdenum, i.e., H_3pterin and dithiocarbamate, is an unprecedented result.

One view of the mechanism of pterin oxidation by DMSO as mediated by molybdenum is offered in Scheme 1. DMSO substitution for chloride is undoubtedly the first step, and this event has been observed for **1**, $MoOCl_3(H_3dmp)$, and $MoOCl_3(H_3biopterin)$ in DMSO solution. The X-ray structure of $MoOCl_3(H_3dmp)$[13] shows that the longest, and presumably weakest, Mo−Cl bond is the site mutually cis to the Mo═O and Mo−N5 bonds as illustrated by Scheme 1. The transfer of an oxygen atom (step b) from DMSO to Mo is the point of formal oxidation of the complex, and we view this step as the transfer of two electrons from the Mo═N5 bond to the incipient Mo═O bond. Prior to further oxidation, the pterin must lose at least two protons to a base (steps c and d); this base is designated :B in Scheme 1. Solution species capable of proton abstraction are either another pterin molecule or a Mo═O group. The Mo═O group is used as a base in Scheme 1 where its sequential protonation (steps d and e) has the illusion of resulting from intramolecular proton transfer between pterin and Mo. Note that these events could also be intermolecular. As a result, the Mo═O group is converted from an oxo ligand via a hydroxo ligand to an aquo group on Mo(VI) in a simultaneous process with

Scheme 1. Possible Mechanism for the Oxidation of Coordinated Reduced Pterin on $MoOCl_3(H_3Pterin)$ by Two Molecules of DMSO



the further oxidation of pterin via electron transfer to molybdenum in steps d and e. This two-electron transfer from pterin to molybdenum (step e) localizes an electron pair between Mo and N5 where it becomes available for a second reduction. Substitution of coordinated water by another DMSO molecule (step f) precedes the reduction (step g) of the second equivalent of DMSO. Overall the reaction is a four-electron oxidation of the molybdenum−pterin complex coupled to the four-electron reduction of two molecules of DMSO.

A similar mechanism may operate in the reduction of DMSO by **1**. The five-electron oxidation observed for complex **1** can be imagined to proceed similarly to the reactions (a−h) in Scheme 1, where the dithiocarbamate chelate replaces two adjacent chloride ligands. Monitoring the progress of DMSO reduction by ^{1}H NMR spectroscopy reveals the sequence of product formation. Oxidized pterin (both 7,8-dihdyro and fully oxidized) appears prior to formation of any TETDS. This suggests that the point where two dithiocarbamate ligands are

(13) Kaufmann, H. L.; Burgmayer, S. J. N.; Carroll, P. J. *Inorg. Chem.* **1999**, *38*, 2600.

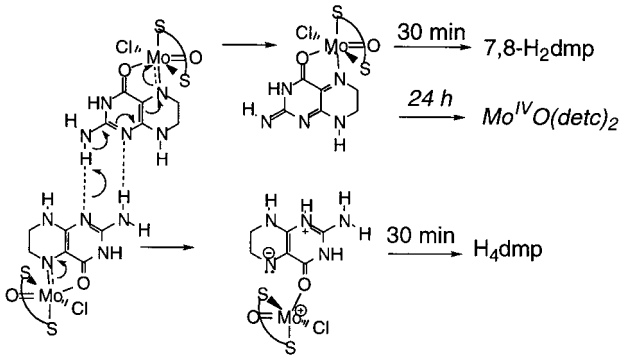


Figure 6. Possible route for pterin oxidation mediated by intermolecular hydrogen bonding in **1**.

oxidized to a disulfide occurs sometime after step g. There are as yet no experimental data to provide mechanistic details of this additional redox step.

In addition to complete oxidation in DMSO solution, compound **1** is reactive in other solvents. The reactivity of **1** in methanol and acetonitrile can best be explained by the conversion of a hydrogen-bonded dimer to a solvated monomer dependent upon the solvent's ability to disrupt the hydrogen bonds. In DMF **1** decomposes to produce oxidized pterin after 2 days, an unexpected result since this reactivity has not been observed for any other reduced pterin complex of molybdenum. As described under Results, the predominant species formed initially in DMF is an hydrogen-bonded dimer. The persistance of the hydrogen-bonded dimer structure in the initial phase of decomposition suggests that pterin oxidation is initiated by an intermolecular deprotonation between coordinated H_3dmp ligands, possibly occurring at the N8 position (Figure 6). This step in turn would cause a redistribution of the electrons in the deprotonated complex, leading to the complete two-electron reduction of one Mo and the oxidation and subsequent dissociation of the pterin in its dihydro form. Note that the intermolecular reaction of two coordinated ligands to yield 7,8-dihydropterin and tetrahydropterin bears strong resemblance to the known disproportionation of trihydropterin radicals producing H_2pterin and H_4pterin.[14] This behavior is furthermore consistent with our preference for considering the two coordinated pterin ligands as "H_3pterin" moieties. The H_2dmp is ultimately further oxidized, possibly by redox reactions with another molecule of **1**. It appears that after the pterin has dissociated, the molybdenum fragment reacts with another Mo fragment to abstract a second dithiocarbamate ligand in order to account for the formation of Mo(IV)O(detc)$_2$. The details of this decomposition remain to be discovered. The significant conclusion meriting a preliminary report in this paper is that hydrogen bonding interactions between the pterins may provide a pathway for electron or proton transfer, allowing for the intermolecular oxidation of the pterin and the reduction of the molybdenum. This conclusion certainly may have parallel in the function of the molybdenum pterinyl-dithiolene of the molybdenum cofactor.[3] In particular it prompts scrutiny of the hydrogen bonding in the molybdopterin region in the multiple crystal structures reported for various molybdoenzymes.[15]

Ten years ago when this project was first begun, the actual structure of the cofactor had not been clearly established. Our original premise was that the pterin may be coordinated directly to the molybdenum in the cofactor. Since this time several molybdoenzyme protein structures have been published which clearly demonstrate molybdenum coordination occurs through the dithiolene of the pterin side chain.[15] These protein structures revealed not only the structure of the cofactor but also that the molybdopterin is probably a participant in the electron transport chain of these enzymes. The pterin portion of the cofactor is held tightly by extensive hydrogen bonding interactions in the enzyme structures. These interactions appear to anchor the cofactor to the protein structure in such a way as to orient the pterin for electron transfer. For example, in aldehyde oxidoreductase,[15b] key hydrogen bonding contacts between the cofactor and protein structure orient the pterin so the N2 position is in close contact with an iron/sulfur cluster which is the next participant in the electron-transfer chain.

The multicontact hydrogen bonding observed in the crystalline state of **1** persists in solution of **1**. Such an extensive connectivity between two metal−pterin complexes is undocumented, though several examples of hydrogen bonding between coordinated pteridines and water molecules and a case of double hydrogen interactions have been reported.[16] Preliminary attempts have been made to isolate **1** with the non-hydrogen bonding counterion BPh_4^- in order to further study the effects of the hydrogen bonding interactions on the reactivity of **1**.

Conclusion

The inclusion of sulfur in the coordination sphere of the molybdenum promotes the unusual reactivity of [MoOCl(detc)-(H_3dmp)]Cl. Although other reduced pterin complexes have been observed to react with DMSO, the observed oxidation of the reduced pterin ligand in DMF is unique. Results from acid/base studies as well as analysis of the solution reactivity strongly suggest that **1** exists as a hydrogen bound dimer in DMSO and DMF which may play an important role in the mechanism for the pterin oxidation observed in these solvents. Hydrogen bonding interactions were observed in the crystal structure of **1** through a quadruple base pair type interaction. This interaction has not been reported for any other metal−pterin complex to our knowledge. Although the mechanism to explain the reactivity of **1** in DMF is unknown at this time, the hydrogen bonding interactions may play an important role in the transfer of electrons and protons necessary in the oxidative pathway of the pterin. The emerging role of the pterin in the cofactor is as a participant in the electron-transfer chain. Thus, the reactivities of **1** and other molybdenum−pterin complexes may be useful models in defining the specific reactivity of the pterin in the cofactor.

Supporting Information Available: Supplementary Information Available. Complete lists of final atomic positions, thermal parameters, bond distances, and bond angles with esd's are located in Supporting Information (7 pages). Ordering information is given on any current masthead page.

IC980881Z

(14) Bobst, A. *Helv. Chim. Acta* **1967**, *50*, 2222.

(15) (a) *E. coli* formate dehydrogenase: Boyington, J. C.; Gladyshev, V. N.; Khangulov, S. V.; Stadtman, T. C.; Sun, P. D. *Science* **1997**, *275*, 1305. (b) *Desulfovibrio gigas* aldehyde oxidoreductase: Romao, M. J.; Archer, M.; Moura, I.; Moura, J. J. G.; LeGall, J.; Engh, R.; Schneider, M.; Hof, P.; Huber, R. *Science* **1995**, *270*, 1170. (c) Huber, R.; Hof, P.; Duarte, R. O.; Moura, J. J. G.; Moura, I.; Liu, M.-Y.; LeGall, J.; Hille, R.; Archer, M.; Romao, M. J. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93*, 8846. (d) *Rhodobacter sphaeroides* DMSO reductase: Schindelin, H.; Kisker, C.; Hilton, J.; Rajagopalan, K. V.; Rees, D. C. *Science* **1996**, *272*, 1615. (e) Chicken liver sulfite oxidase: Kisker, C.; Schindelin, H.; Pacheco, A.; Wehbi, W.; Garrett, R.; Rajagopalan, K. V.; Enemark, J. H.; Rees, D. C. *Cell* **1997**, *91*, 973.

(16) (a) Mitsumi, M.; Toyoda, J.; Nakasuji, K.; Kanehisa, N.; Kai, Y. *Mol. Cryst. Liq. Cryst.* **1996**, *276*, 229. (b) Mitsumi, M.; Toyoda, J.; Nakasuji, K. *Inorg. Chem.* **1995**, *34*, 3367.