Monooxomolybdenum(IV) Complex with Extremely Bulky Dithiolate Ligands — Acceleration of O-atom Transfer by Distorted Square Pyramidal Conformation

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$Q_2[Mo^{IV}O\{1,2\text{-}S_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}_2]$ (Q = NEt_4 (**1**), PPh_4 (**2**)) was synthesized and characterized as a model for Mo-enzymes. The crystal structure of **2** shows the slightly distorted square pyramidal core, $Mo^{IV}OS_4$. The O-atom transfer reaction from Me_3NO to Me_3N in the presence of **1** proceeds at 30 to 48 times higher rates than in the presence of $[Mo^{IV}O\{1,2\text{-}S_2\text{-}(C_6H_4)\}_2]^{2-}$ (**3**).

Molybdenum enzymes and related tungsten enzymes, which are known to undergo O-atom transfer, are of great interest because they have a unique core structure and can act upon diverse substrates.[1] Their active sites characteristically have one or two pterin dithiolene ligands, which cannot be found in other metalloenzymes, and one or two oxo ligands. In Figure 1, the active site of arsenite oxidase from *Alcaligenes faecalis* is illustrated.[2] Arsenite oxidase can be assigned to the dimethylsulfoxide (DMSO) reductase family. The $Mo^{IV}OS_4$ core in the reduced state has a distorted square pyramidal structure; the C1–C2–C3–C4 dihedral angle is about 14°. Many model complexes with a $Mo^{IV}OS_4$ core have been synthesized but with an approximately regular square pyramidal sturucture.[3] In this study, we synthesized novel monooxomolybdenum complexes (**1**, **2**) using an extremely bulky dithiolate ligand, $[1,2\text{-}S_2\text{-}3,6\text{-}(Ph_3CCONH)_2\text{-}C_6H_2]^{2-}$ (Figure 1), to clarify the relationship between function and distorted structure.

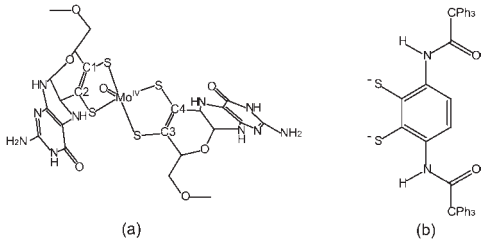

Figure 1. (a) Distorted square pyramidal structure of active site in arsenite oxidase. (b) Synthetic bulky dithiolate ligand.

Synthesis of **1** or **2** involved a ligand-exchange reaction of $(NEt_4)[Mo^{V}O(SPh)_4]$ or $(PPh_4)[Mo^{V}O(SPh)_4]$[4] with $\{1,2\text{-}S_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}_2$,[5] accompanied with reduction by NEt_4BH_4.[6]

In Figure 2, the crystal structure of the anion part of **2**·$8CH_3CN$ is shown.[7] The space-filling representation clearly shows that the bulky triphenyl groups form a unique conformation like as two engaged gears to avoid their steric hindrance. The C11–C12–C31–C32 dihedral angle of **2** is 5.6°, which is slightly larger than that of **3** (5.0° and 2.7° for two structures in a unit cell).[8] The amide groups are not coplanar with the benzene rings and the C(amide)–N–C(benzene ring)–C(benzene ring) dihedral angles are 5–25°. Considering the orientation of the amide groups and the short N–S distances (2.92–2.97 Å), NH···S hydrogen bonding is expected. Large differences between **2** and **3** are not observed for other bond lengths and angles.

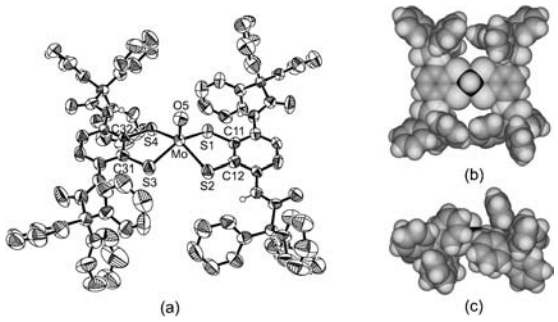

Figure 2. Structure of the anion part of **2**·CH_3CN. (a) ORTEP perspective. (b) Space-filling view (top). (c) Space-filling view (side).

2 shows a single broad NH band at 3291 cm^{-1} in the solid state, the low-frequency-shifted band indicates the presence of NH···S hydrogen bonding,[9] as expected from the crystal structure of **2**.

The shifts of the Mo=O in **1** from that of **3** are +24 cm^{-1} for the resonance Raman band and +23 cm^{-1} for the IR band, whereas the Mo–S Raman band shifts +10 cm^{-1} from that of **3**. The LMCT band (348 nm) of **1** in DMF solution is red-shifted by 20 nm from **3** (328 nm).[10] The Mo^{IV}/Mo^{V} redox potential of **1** in DMF solution is positively shifted by 0.41 V from **3** (−0.38 V vs SCE). As compared with L = $1,2\text{-}S_2\text{-}C_2(CH_3)_2$, enhancements of Mo=O, red-shifts, and positive shifts are observed for $[Mo^{IV}OL_2]^{2-}$ (L = $1,2\text{-}S_2\text{-}C_2(COOCH_3)_2$, $1,2\text{-}S_2\text{-}C_2(CF_3)_2$, $1,2\text{-}S_2\text{-}C_2(CN)_2$) with electron-withdrawing substituents.[11] Because the inductive effect of the triphenylacetoamido group is thought to be weak,[12] the delocalization of charge on sulfur atoms by NH···S hydrogen bonding should be the main reason of these shifts.

Figure 3 shows the spectroscopic time course of the O-atom-transfer reaction between **1** and Me_3NO, one of the substrates for

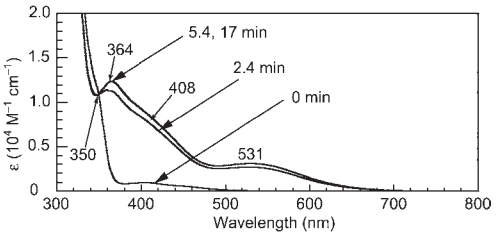

Figure 3. Visible spectral change during O-atom-transfer reaction in DMF at 27 °C with $[\mathbf{1}]_0$ = 1 mM and $[Me_3NO]_0$ = 2 mM.

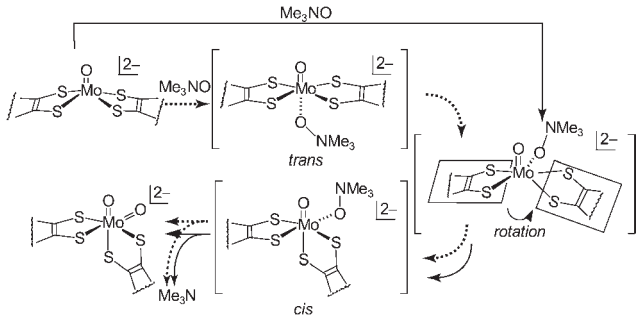

Figure 4. Proposed mechanism of O-atom-transfer reaction between dithiolene complexes, **1** (———) or **3** (· · · · · ·), and Me_3NO.

the DMSO reductase family.[13] Trimetylamine *N*-oxide reductase is crystallographically characterized only in the oxidized form; two pterin dithiolene, two oxo, and Oγ of Ser147 are revealed to be the ligands.[13] **1** reacts quickly with Me_3NO to give $[Mo^{VI}O_2\{1,2\text{-}S_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}_2]^{2-}$ and Me_3N. The initial rate constant (k_{obs}) is analyzed by pseudo-first-order kinetics using the LMCT band (531 nm) for the $Mo^{VI}O_2$ complex. The isosbestic point is observed at 350 nm. The k_{obs} ($0.026\,s^{-1}$) for **1** (1 mM) is 48 times larger than that of **3** in the presence of 2 mM Me_3NO.[10] The k_{obs} for **1** increases to $0.17\,s^{-1}$ at 10 mM Me_3NO and is 30 times larger than **3**.

Previously, we reported that the Mo^{IV} complex with intermolecular NH···S hydrogen bonding accelerates Me_3NO reduction by about 6 times.[14] However, it is not explainable that the large acceleration exhibited by **1** is caused only by the presence of NH···S hydrogen bonding. In the case of $[Mo^{IV}O(1,2\text{-}1,2\text{-}S_2\text{-}3\text{-}Ph_3SiC_6H_3)_2]^{2-}$ with bulky ligands, the *trans–cis* rearrangement is the rate-determining step in the proposed reaction mechanism of **3** (Figure 4).[10] However, **1** did not show such a rate-determining step in spite of much bulkier ligands. Therefore, a new reaction mechanism for **1** should be proposed in Figure 4. In solution, the free rotation of Ph–C and C–C(=O) bonds in Ph_3C–C(=O)–NH and the increase of the C(amide)–N–C(benzene ring)–C(benzene ring) dihedral angles by thermal vibration create temporarily more distortion than in the solid state. But, in the cis form, such steric repulsion is decreased. Thus, the extremely large oxidation rate for **1** is attributed to the release from the distortion. The initial step of the reaction is considered to be Me_3NO attack to a vacant space cis to the oxo ligand, formed by the distortion. Such cis-attack is discussed for the active site in Mo-, W-enzymes.[15]

Recently a distorted square pyramidal structure has also been reported in the active center of dithionite-reduced DMSO reductase from *Rhodobacter capsulatus*.[16] The Mo center in the reduced form is hexacoordinated with two dithiolenes, an oxo ligand, and Oγ of Ser147. The dihedral angle of four carbon atoms in two dithiolenes is about 31°. The large distortion from the square pyramidal conformation in the active site of DMSO reductase will accelerate the O-atom transfer from $Mo^{IV}O$ to $Mo^{VI}O_2$.

References and Notes

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5 Ligand synthesis is as follows. $(n\text{-}Bu_4N)_2\{1,2\text{-}(S_2O_3)_2\text{-}3,6\text{-}(NH_2)_2C_6H_2\}$ was derived from a cation-exchange reaction of $K_2\{1,2\text{-}(S_2O_3)_2\text{-}3,6\text{-}(NH_2)_2C_6H_2\}$[17] and *n*-$Bu_4NBr$ using a liquid–liquid extraction. To a chloroform solution (30 mL) of $(n\text{-}Bu_4N)_2\{1,2\text{-}(S_2O_3)_2\text{-}3,6\text{-}(NH_2)_2C_6H_2\}$ (1.0 g, 1.2 mmol) including Et_3N (0.84 mL, 6.0 mmol) was slowly added Ph_3CCOCl (0.90 g, 2.9 mmol), which is synthesized from Ph_3COOH and thionyl chloride. The mixture was stirred overnight at reflux. The solution was then cooled to room temperature and washed with water (100 mL) and dried over Na_2SO_4. The solution was concentrated in volume to 5 mL, and then diethyl ether (30 mL) was added. The resulting white powder of $(n\text{-}Bu_4N)_2\{1,2\text{-}(S_2O_3)_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}$ was collected and washed with diethyl ether. $(n\text{-}Bu_4N)_2\{1,2\text{-}(S_2O_3)_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}$ (620 mg, 0.46 mmol) and *i*-PrSNa (380 mg, 3.9 mmol) were suspended in methanol (20 mL), and the reaction mixture was heated at reflux for 12 h under Ar. Ethanol was evaporated under reduced pressure. The residue was dissolved in dichloromethane (100 mL). The solution was washed with brine, 2% HCl, brine, 4% $NaHCO_3$, and brine; dried over Na_2SO_4; and concentrated in vacuo. The residual solid was dissolved in methanol (30 mL), and the solution was heated under reflux overnight. The obtained yellow precipitate of $\{1,2\text{-}S_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}_2$ was collected with filtration and washed with methanol and diethyl ether. Yield, 130 mg (20%); Anal. Calcd for $C_{92}H_{68}N_4O_4S_4$: C, 77.72; H, 4.82; N, 3.94. Found: C, 76.86; H, 4.76; N, 4.02%. IR (KBr): ν_{NH} 3361, 3345, 3316, $\nu_{C=O}$ 1704, $1685\,cm^{-1}$.
6 **1** was synthesized as follows: An acetonitrile (5 mL) solution of $\{1,2\text{-}S_2\text{-}3,6\text{-}(Ph_3CCONH)_2C_6H_2\}_2$ (100 mg, 0.29 mmol) and NEt_4BH_4 (45 mg, 0.31 mmol) was added with stirring to a solution of $(NEt_4)[Mo^{V}O(SPh)_4]$ (100 mg, 0.15 mmol) in a mixed solvent of acetonitrile (10 mL) and water (1 mL), resulting in the formation of a yellow powder that was collected with filtration. The obtained yellow powder of **1** was washed with acetonitrile and diethyl ether and dried in vacuo. Yield, 230 mg (87%); Anal. Calcd for $C_{108}H_{108}N_6O_5MoS_4$: C, 72.30; H, 6.07; N, 4.68. Found: C, 69.26; H, 6.14; N, 5.06%. Absorption spectrum (DMF): λ_{max} ($\varepsilon\,M^{-1}\,cm^{-1}$) 348 (12000), 406 (*sh*) (980), 457 (530) nm. IR (KBr): ν_{NH} 3332, 3315, 3280, $\nu_{C=O}$ 1680, $\nu_{Mo=O}$ $928\,cm^{-1}$. Raman: $\nu_{Mo=O}$ 926, $\nu_{Mo\text{–}S}$ $366\,cm^{-1}$. ^1H NMR (DMF-d_7, anion): δ 9.34 (s, 4), 7.97 (s, 4), 7.49 (d, 24), 7.37 (t, 24), 7.26 (t, 12). Using a PPh_4 cation, **2** was synthesized by a similar method described for **1**. Calcd for $C_{116}H_{108}N_4O_5P_2MoS_4$: C, 76.00; H, 4.92; N, 2.53. Found: C, 73.67; H, 5.08; N, 2.45%.
7 Crystal data for **2**·$8CH_3CN$. $C_{156}H_{132}N_{12}O_5P_2S_4Mo$, $M_r = 2540.86$, monoclinic, $P2_1/n$, $a = 26.071(6)$, $b = 14.944(2)$, $c = 35.217(8)$ Å, $\beta = 93.81(2)°$, $Z = 4$, $V = 13691(5)$ Å^3, $D_{calcd} = 1.233\,gcm^{-3}$, $\mu = 0.240\,mm^{-1}$, 18479 reflections measured, 17861 independent ($R_{int} = 0.1034$), $R1 = 0.0672$ ($I > 2\sigma(I)$), $wR2 = 0.2347$ (all data).
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