J|A|C|S
COMMUNICATIONS

Oxygen Transfer from Sulfoxides: Oxidation of Alkylarenes Catalyzed by a Polyoxomolybdate, $[PMo_{12}O_{40}]^{3-}$

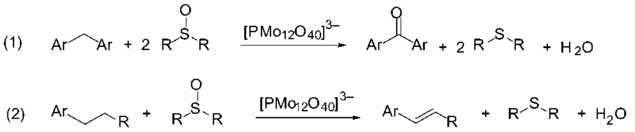
Alexander M. Khenkin and Ronny Neumann*

Department of Organic Chemistry, Weizmann Institute of Science, Rehovot 76100, Israel

Received December 23, 2001

Oxygen transfer reactions are of basic importance in both organic-synthetic and biological settings. In this context, the use of sulfoxides as oxidants is also of significant interest. Notably, in synthetic organic chemistry, the Swern reaction and its numerous variants use sulfoxides, primarily DMSO, for the oxidation of alcohols to aldehydes and ketones.[1] The oxidation reaction is not catalytic and requires a stoichiometric amount of an electrophilic reagent. In addition, deoxygenation of sulfoxides to sulfides catalyzed by metal complexes with oxygen transfer to the metal complex or to reduced species such as hydrohalic acids, phosphines, carbenes, and carbon monoxide is also well established.[2] Despite these well-known cases describing oxygen-transfer reactions with sulfoxides, to the best of our knowledge, there have been no reports of catalytic oxygen transfer from a sulfoxide to a hydrocarbon.

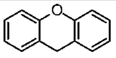
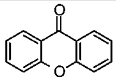
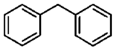
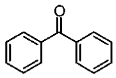
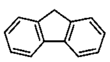
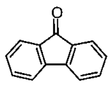
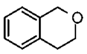
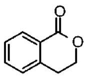
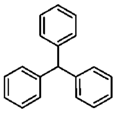
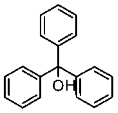
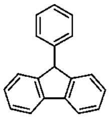
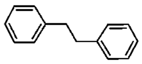
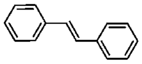
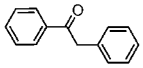
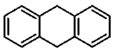
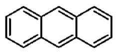
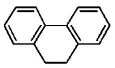
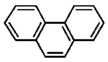
In the context of ongoing interest in the catalytic activity of polyoxometalates in oxidation reactions with various oxygen donors,[3] we have now found that polyoxometalates can also activate sulfoxides and lead to oxidation of alkylarenes. Specifically, the oxidized Keggin-type polyoxomolybdate, $^4Q_3[PMo^{VI}_{12}O_{40}]$ ($^4Q = n\text{-}C_4H_9N^+$), catalyzes the oxidation of alkyl aromatics to ketones, eq 1, or alternatively catalyzes their oxydehydrogenation, eq 2.



In Table 1, the results on the oxidation of alkylarenes with phenylmethylsulfoxide (PMSO) catalyzed by $^4Q_3[PMo_{12}O_{40}]$ are presented.[4] For secondary alkylarene substrates without hydrogen α to the benzylic position, there was oxygenation at the benzylic position and selective formation of the diaryl ketone. The oxygenation of triphenylmethane was not selective (see below). For other substrates, 9,10-dihydroanthracene, 9,10-dihydrophenanthrene, and 1,2-diphenylethane, the presence of the α-hydrogen instead led mostly to oxydehydrogenation. The reaction stoichiometry as indicated in eqs 1 and 2 was verified within ±10% by gas chromatography. The catalyst was stable under reaction conditions as surveyed by following the ^{31}P NMR spectrum.

Use of the oxidation of xanthene to xanthen-9-one as a model reaction also enabled the observation of the effect of the sulfoxide structure and the catalyst on the reactivity. With use of the following reaction conditions—0.2 M xanthene, 1 M sulfoxide, 3.3 mM $^4Q_3[PMo_{12}O_{40}]$ in 1,2-dichlorobenzene (DCB) at 170 °C, Ar, 2 h—the relative reactivity for various sulfoxides related to PMSO was the following: dimethyl sulfoxide (DMSO), 0.4 < diphenylsulfoxide (DPSO), 0.8 < phenylmethylsulfoxide (PMSO), 1.0 < 4-nitrophenylmethylsulfoxide (NPMSO), 1.2. On one hand, the results indicate that electron-withdrawing groups increase reactivity, NPMSO > PMSO > DMSO. On the other hand, a steric effect is also apparent; i.e., DPSO is less reactive than PMSO. Other molybdates, such as $^4Q_2MoO_4$ and $^4Q_6Mo_7O_{24}$, were significantly less active catalysts per Mo atom compared to $^4Q_3[PMo_{12}O_{40}]$. $MoO_2(acac)_2$ was initially reactive but quickly yielded an unidentified black precipitate. The analogous polyoxotungstate, $^4Q_3[PW_{12}O_{40}]$, was inactive. Some insight into the reaction mechanism is most warranted. Thus, the rates of oxygenation of xanthene, 9,10-dihydroanthracene, diphenylmethane, fluorene, and triphenylmethane were plotted as a function of the oxidation potential,[5] the homolytic benzylic C−H bond energy,[6] and the heterolytic benzylic C−H bond energy,[7] Figure 1.

Table 1. Oxidation of Alkylarenes with PMSO Catalyzed by $^4Q_3[PMo_{12}O_{40}]^a$

Substrate	Product	Conversion	TON
		96	145
		92	142
		44	67
		40	61
	 30%  70%	46	70
	 86%  14%	9	26
		100	300
		18	55

[a] Reaction conditions: 1 mmol of PMSO, 1 mmol of substrate, 3.3 μmol of $Q_3PMo_{12}O_{40}$ in 1 mL of DCB, 170 °C, 15 h, Ar. Conversion is mol % of PMSO reacted, TON is mol of products from alkylarene/mol of $Q_3PMo_{12}O_{40}$.

Clearly, the best correlation ($r^2 = 0.99$) was for the rate as a function of the heterolytic benzylic C−H bond energy with an obvious deviation for triphenylmethane. This correlation suggests that hydride abstraction and formation of a benzylic carbocation is involved in the reaction pathway and tends to discount alkylarene

10.1021/ja0178721 CCC: $22.00

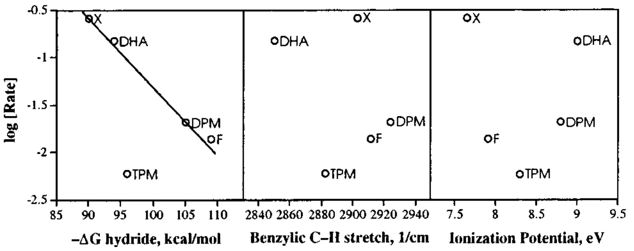
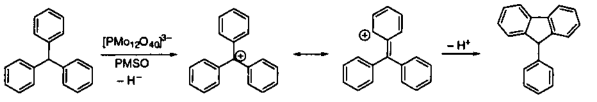


Figure 1. The rate of alkylarene oxygenation as a function of heterolytic and homolytic C−H bond strength, and oxidation potential. Reaction conditions: 1 mmol PMSO, 1 mmol substrate, 3.3 μmol $Q_3PMo_{12}O_{40}$, 170 °C, Ar. The initial rates were computed as −d[substrate]/d*t* and were 0.26, 0.15, 0.021, 0.014, and 0.006 mmol/h for xanthene (X), 9,10-dihydroanthracene (DHA), diphenylmethane (DPM), fluorene (F), and triphenylmethane (TPM), respectively.

Scheme 1. Formation of 9-Phenylfluorene from Triphenylmethane



activation by hydrogen abstraction or electron-transfer pathways. The formation of the carbocation is corroborated by the observation of 9-phenylfluorene as the major product in the reaction of triphenylmethane, Scheme 1.[8] This reaction along with the difference in the oxygen transfer step and reaction stoichiometry, eq 1, probably account for the outlying result observed for triphenylmethane. A kinetic isotope effect (k_H/k_D) of 3.4 for the oxygenation of xanthene/xanthene-d_2 was also measured in support of C−H bond cleavage in the rate-determining step.

Isotope-labeling experiments also gave significant insight. First, the ^{17}O NMR of a solution of 1.4 M PMSO-^{17}O (~0 ppm, ~8% enriched)[9] and 2.8 mM $^4Q_3[PMo_{12}O_{40}]$ in DCB showed a new peak at 181 ppm, indicating a coordination interaction between PMSO and the polyoxomolybdate. This chemical shift is distinctly different compared to chemical shifts for bridging and terminal oxygens, ~550 and ~930 ppm,[10] and rules out oxygen exchange between the sulfoxide and $^4Q_3[PMo_{12}O_{40}]$. Second, a reaction between 1 M PMSO-^{18}O (85% enriched),[9] 0.2 M xanthene, and 3.3 mM $Q_3PMo_{12}O_{40}$ in DCB at 170 °C yielded xanthene-9-one with 62% ^{18}O enrichment. Third, a reaction between 1 M PMSO-^{16}O, 0.2 M xanthene, and 3.3 mM $Q_3PMo_{12}O_{40}$ in DCB at 170 °C in the presence of 1 mmol $H_2{}^{18}O$ (95% enrichment) gave xanthen-9-one with 36% ^{18}O; however, the PMSO remained unlabeled. Independently, PMSO was not labeled with $H_2{}^{18}O$ in the presence or absence of $Q_3PMo_{12}O_{40}$.

The kinetics of the oxygenation reaction was also studied. In the oxygenation of xanthene with PMSO catalyzed by $Q_3PMo_{12}O_{40}$, the reaction displayed Michaelis−Menten-type kinetic behavior as a function of PMSO concentration, Figure 2. A weak binding constant, $K_m = 1$ M, between PMSO and the polyoxometalate was computed. Additionally, van't Hoff plots (Supporting Information) showed the reaction to be of simple first order in xanthene and also approximately first order in $Q_3PMo_{12}O_{40}$. An Arrhenius plot (Supporting Information) yielded the following activation parameters: $E_a = 12.85$ kcal/mol; $\Delta H^{\ddagger}_{25°C} = 12.26$ kcal/mol; $\Delta S^{\ddagger}_{25°C} = -22.0$ cal/(mol K).

From the experimental evidence a conceivable reaction pathway for oxygen transfer may be postulated as follows. First, a $Q_3PMo_{12}O_{40}$−sulfoxide complex is formed (^{17}O NMR, Michaelis kinetics). No reaction occurs in the absence of either polyoxometalate or sulfoxide. This complex catalyzes hydride abstraction, yielding a carbocation intermediate (Figure 1, formation of 9-phenylfluorene from triphenylmethane and the positive effect of electron-withdrawing groups in the sulfoxide) and a reduced polyoxometalate. Then the carbocation is oxygenated by the sulfoxide (^{18}O-labeling experiments) to give the oxygenated product and a proton is released. Water may exchange with an intermediate formed at this stage. The reduced polyoxometalate is reoxidized quickly[11] by an additional equivalent of sulfoxide to yield the oxidized $Q_3PMo_{12}O_{40}$, sulfide, and water. The quantitative formation of the latter (GC-MS) was verified by using ^{18}O-labeled PMSO.

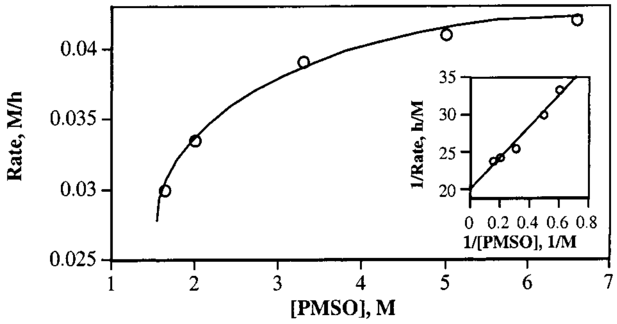


Figure 2. The rate of xanthene oxygenation as a function of initial PMSO concentration. Reaction conditions: 0.6 M xanthene, 1.65−6.6 M PMSO, 10 mM $Q_3PMo_{12}O_{40}$ in DCB at 170 °C. The insert is the Lineweaver−Burk plot ($r^2 = 0.97$); maximum rate, 0.05 M/h; Michaelis constant, K_m = 1 M.

Acknowledgment. This research was supported by the Basic Research Foundation administered by the Israeli Academy of Science and Humanities and the Israel Ministry of Science.

Supporting Information Available: The reaction kinetics of xanthene oxygenation as a function of xanthene and polyoxometalate concentration, and reaction temperature (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Mancuso, A. J.; Swern, D. *Synthesis* **1981**, 165−185. Tidwell, T. T. *Org. React.* **1990**, *39*, 297−572. Tidwell, T. T. *Synthesis* **1990**, 857−870.
(2) Kukushkin, V. Y. *Coord. Chem. Rev.* **1995**, *139*, 375−407.
(3) Mizuno, N.; Misono, M. *Chem. Rev.* **1998**, *98*, 171−199. Hill, C. L.; Prosser-McCartha, C. M. *Coord. Chem. Rev.* **1995**, *143*, 407−455. Kozhevnikov, I. V. *Chem. Rev.* **1998**, *98*, 171−198. Neumann, R. *Prog. Inorg. Chem.* **1998**, *47*, 317−370.
(4) Reactions were carried out in 20 mL glass Schlenk flasks. The flasks were loaded with the appropriate components and degassed by 3 successive "freeze−thaw−pump" cycles and filled with dry Ar. The reactions were carried out in a thermostated oil bath and analyses were carried out by GC and GC-MS.
(5) The oxidation potential is assumed to be proportional to the ionization potential of the hydrocarbon. The data are from NIST at http://webbook.nist.gov/chemistry.
(6) The energy of the homolytic bond disassociation is assumed to be proportional to the gas-phase IR absorption of the benzylic C−H bond. The data are from NIST at http://webbook.nist.gov/chemistry.
(7) $-\Delta G_{\text{hydride}}$ is the free energy of R−H heterolytic bond disassociation: $R-H \rightarrow R^+ + H^-$. Data from: Cheng, J. P.; Handoo, K. L.; Parker, V. D. *J. Am. Chem. Soc.* **1993**, *115*, 2655−2660. Handoo, K. L.; Cheng, J. P.; Parker, V. D. *J. Am. Chem. Soc.* **1993**, *115*, 5067−5072.
(8) In a control experiment, reaction of the authentic carbocation, trityl tetrafluorborate, at reaction conditions as given in Table 1, yielded triphenylmethanol/9-phenylfluorene in a 26/74 ratio, very similar to the 30/70 ratio observed in the oxidation reaction
(9) ^{17}O- and ^{18}O-labeled PMSO were prepared with $H_2{}^{17}O$ (10.2% ^{17}O) and $H_2{}^{18}O$ (95% ^{18}O), using the procedure described in: Okruszek, A. *J. Label. Compd. Radiopharm.* **1983**, *20*, 741−743.
(10) Filowitz, M.; Ho, R. K. C.; Klemperer, W. G.; Shum, W. *Inorg. Chem.* **1979**, *18*, 93−103.
(11) Reduced $H_2Q_3PMo_{12}O_{40}$ (prepared by reduction of $Q_3PMo_{12}O_{40}$ with Zn/HCl) is oxidized by PMSO at rates that are at least 2 orders of magnitude faster than the oxidation of xanthene.

JA0178721