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Acid-Catalyzed Photoreduction of Dialkyl Sulfoxides by an Acid-Stable NADH Analogue

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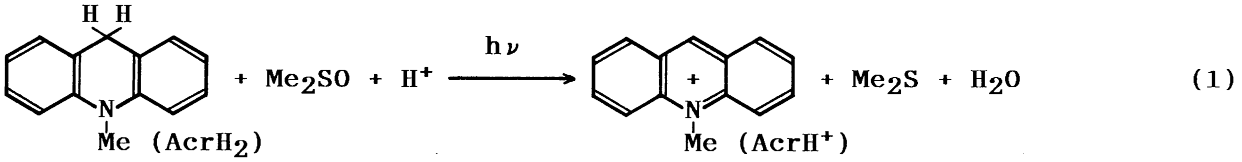
Photoreduction of dialkyl sulfoxides by an acid-stable NADH analogue, 9,10-dihydro-10-methylacridine ($AcrH_2$), proceeds in the presence of perchloric acid in acetonitrile via photoinduced electron transfer from the singlet excited state of $AcrH_2$ to protonated sulfoxides to yield the corresponding dialkyl sulfides.

We have recently reported that a number of substrates can be reduced readily by an acid-stable NADH analogue, 9,10-dihydro-10-methylacridine ($AcrH_2$) in the presence of $HClO_4$ in acetonitrile (MeCN).1) The use of the excited states of NADH analogues is effective for the reduction of various substrates by NADH analogues.2) On the other hand, dimethyl sulfoxide (DMSO) being widely used as a solvent is inert towards NADH analogues being mild reductants, and thereby no non-enzymatic reduction of DMSO by NADH analogues has so far been reported.3) In this study we report that the use of the excited state of $AcrH_2$ not alone, but combined with the acid catalysis makes it possible for the first time to reduce dialkyl sulfoxides by $AcrH_2$ to the corresponding dialkyl sulfides.

The $AcrH_2$ shows no reactivity towards DMSO in the presence of $HClO_4$ in MeCN in the dark. No photoreduction of DMSO by $AcrH_2$ has occurred in the absence of $HClO_4$ in MeCN, either. When the presence of $HClO_4$ and photo-irradiation are combined together, however, DMSO can be reduced by $AcrH_2$ to yield 10-methylacridinium ion ($AcrH^+$) and dimethyl sulfide (Eq. 1).4)



(1)

Other dialkyl sulfoxides [Bu_2SO, $(PhCH_2)_2SO$] are also reduced by $AcrH_2$ in the presence of $HClO_4$ in MeCN under photo-irradiation as shown in Table 1.

Table 1. Photoreduction of dialkyl sulfoxides (0.10 mol dm^{-3}) by $AcrH_2$ (5.7 x 10^{-2} mol dm^{-3}) in the presence of $HClO_4$ and H_2O (0.50 mol dm^{-3}) in MeCN at 298 K under irradiation with a xenon lamp

Substrate	$[HClO_4]$ / mol dm^{-3}	Product (yield/%)[a]
Me_2SO	0	No reaction
Me_2SO	0.20	$AcrH^+$ (90) Me_2S (87)
Bu_2SO	0	No reaction
Bu_2SO	0.20	$AcrH^+$ (92) Bu_2S (92)
$(PhCH_2)_2SO$	0	No reaction
$(PhCH_2)_2SO$	0.20	$AcrH^+$ (92) $(PhCH_2)S$ (92)

a) Irradiation time: 20 h.

In the presence of $HClO_4$ (70%, 0.20 mol dm^{-3}) both $AcrH_2$ and R_2SO are readily protonated in MeCN judging from the change in their electronic absorption and ^1H NMR spectra in the presence of $HClO_4$.[5,6] When H_2O (0.50 M) is added to the MeCN solution, however, only R_2SO is protonated while no protonation of $AcrH_2$ takes place. From the change in the absorbance due to R_2SO (λ = 220 nm) in the presence of $HClO_4$ in MeCN containing H_2O (0.50 M) the protonation equilibrium constants K ($R_2SO + H^+ \rightleftharpoons R_2SOH^+$) are determined as 8.0 x 10^2 and 5.0 x 10^3 dm^3 mol^{-1} for Me_2SO and Bu_2SO, respectively. The protonation of R_2SO may enhance the oxidizing ability significantly as reported for the case of flavin analogues.[7] In fact, the fluorescence of $AcrH_2$ is readily quenched by R_2SO in the presence of $HClO_4$, although no quenching has been observed in the absence of $HClO_4$. The fluorescence quenching in the presence of $HClO_4$ may occur by electron transfer from $^1AcrH_2^*$ to the protonated species, R_2SOH^+ (Eq. 2), since no

$$^1AcrH_2^* + R_2SOH^+ \xrightarrow{k_{et}} AcrH_2^{+\cdot} + R_2\dot{S}OH \qquad (2)$$

deuterium isotope effect has beenobserved when $AcrH_2$ is replaced by the 9,9'-dideuterated compounds ($AcrD_2$).

The fluorescence of $^1AcrH_2^*$ is also quenched by $HClO_4$ probably due to the protonation of the singlet excited state, which is non-fluorescent (Eq. 3). This is a dynamic quenching process, since the quenching constant

$$^1AcrH_2^* + H^+ \xrightarrow{k_H} AcrH_3^{+*} \qquad (3)$$

agrees with that determined from the lifetime measurements of $^1AcrH_2^*$ in the presence of $HClO_4$. The rate constant k_H is determined as 6.1×10^9 dm^3 mol^{-1} s^{-1}. When $^1AcrH_2^*$ is quenched by both R_2SOH^+ and $HClO_4$, a modified Stern-Volmer relation is derived for the ratio of the fluorescence intensities in the absence and presence of R_2SO at various initial concentrations $[HClO_4]_0$, I_0/I and $[R_2SOH^+]$ as given by Eq. 4,

$$(1 + k_H \tau_0[HClO_4]_0)(I_0/I - 1) = (k_{et} - k_H)\tau_0[R_2SOH^+] \qquad (4)$$

where τ_0 is the lifetime of $^1AcrH_2^*$ (7.0 ns) in MeCN containing H_2O (0.50 mol dm^{-3}). The validity of Eq. 4 is confirmed by linear plots between $(1 + k_H \tau_0[HClO_4]_0)(I_0/I - 1)$ and $[R_2SOH^+]$ as shown in Fig. 1, where the $[R_2SOH^+]$ values are obtained by using the K values of the protonation of R_2SO (vide supra). From the slopes in Fig. 1 are determined the rate constants (k_{et}) of electron transfer from $^1AcrH_2^*$ to Me_2SOH^+ and Bu_2SOH^+ as 1.0×10^{10} and 1.1×10^{10} dm^3 mol^{-1} s^{-1}, respectively.

The quantum yields (Φ) of the photoreduction of R_2SO by $AcrH_2$ and $AcrD_2$ in the presence of $HClO_4$ in MeCN were determined by using an iron(III) oxalate actinometer.[8,9] The Φ value increases with an increase in the $HClO_4$ concentration to reach a maximum value and then decreases in the high $HClO_4$ concentrations as shown in Fig. 2. The increase in the Φ value corresponds to the increase in $[R_2SOH^+]$ which reaches a constant value when all R_2SO molecules are protonated. The inhibitory effect of $HClO_4$ in high $[HClO_4]$ in Fig. 2 may be ascribed to the quenching of $^1AcrH_2^*$

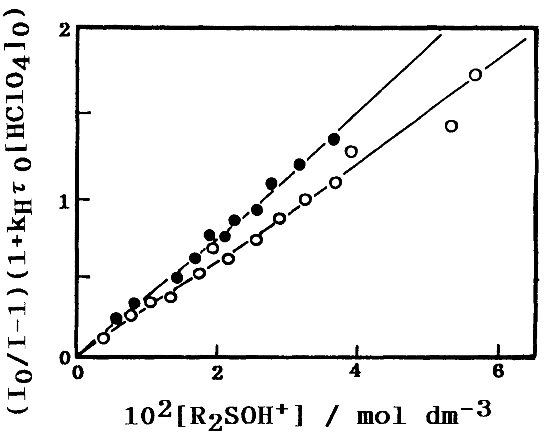


Fig. 1. Plots of $(I_0/I - 1)(1 + k_H \tau_0[HClO_4])$ vs. $[R_2SOH^+]$ for photoinduced electron transfer from $^1AcrH_2^*$ to R_2SO, R = Me (○) and Bu (●) in the presence of $HClO_4$ in MeCN containing H_2O (0.50 mol dm^{-3}) at 298 K.

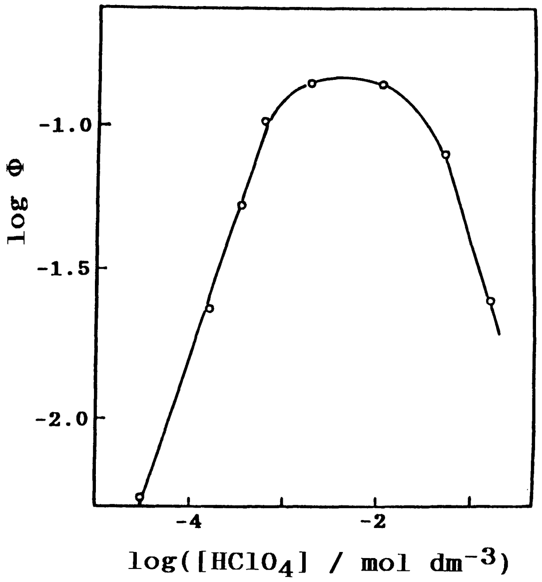
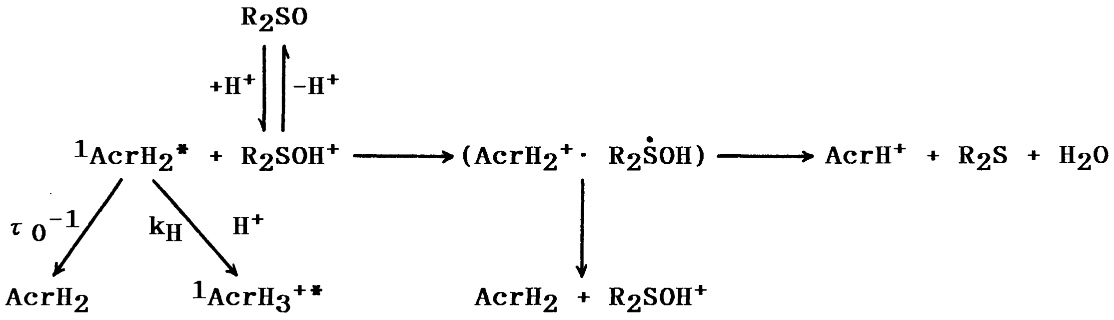


Fig. 2. Dependence of log Φ on $\log[HClO_4]$ for the photoreduction of Me_2SO (3.4×10^{-3} mol dm^{-3}) by $AcrH_2$ (2.0×10^{-3} mol dm^{-3}) in the presence of $HClO_4$ in MeCN containing H_2O (0.50 mol dm^{-3}) at 298 K under irradiation of light of λ = 320 nm.

by $HClO_4$ (Eq. 2). No primary kinetic isotope effect on the Φ value has been observed when $AcrH_2$ is replaced by $AcrD_2$. Thus, the reaction mechanism may be summarized as shown below. The acid-catalyzed photoinduced electron transfer from $^{1}AcrH_2^*$ to R_2SOH^+, which is the rate-determining step, may be followed by the facile hydrogen transfer from $AcrH_2^{+\cdot}$ to $R_2\dot{S}OH$, yielding $AcrH^+$ and R_2S after removal of H_2O, in competition with the back electron transfer from $R_2\dot{S}OH$ to $AcrH_2^{+\cdot}$. In the absence of $HClO_4$ no reaction is started, since the electron acceptor ability of R_2SO is not strong enough to accept an electron from $^{1}AcrH_2^*$.



References

1) S. Fukuzumi, S. Mochizuki, and T. Tanaka, J. Am. Chem. Soc., 111, 1497 (1989); S. Fukuzumi, M. Chiba, and T. Tanaka, Chem. Lett., **1989**, 31; M. Ishikawa and S. Fukuzumi, J. Chem. Soc., Chem. Commun., **1990**, 1353.

2) S. Fukuzumi and T. Tanaka, "Photoinduced Electron Transfer," ed by M. A. Fox and M. Chanon, Elsevier, Amsterdam (1988), Part C, pp. 578-636.

3) The pathway of DMSO metabolism involves the initial reduction to dimethyl sulfide by NADH being an electron donor; J. A. M. de Bont, J. P. van Dijken, and W. Harder, J. Gen. Microbiol., 127, 315 (1981); H.-C. Yen and B. Marrs, Arch. Biochem. Biophys., 181, 411 (1977); S. H. Zinder and T. D. Brock, J. Gen. Microbiol., 105, 335 (1978).

4) The quantitative formation of $AcrH^+$ and dialkyl sulfide has been confirmed by the GLC analysis as well as the measurements of the ^{1}H NMR spectra.

5) S. Fukuzumi, K. Ishikawa, and T. Tanaka, Tetrahedron, 42, 1021 (1986).

6) F. G. Bordwell, Acc. Chem. Res., 21, 456 (1988).

7) S. Fukuzumi, S. Kuroda, and T. Tanaka, J. Am. Chem. Soc., 83, 1867 (1985).

8) C. G. Hatchard and C. A. Parker, Proc. R. Soc. London, Ser. A, 235, 518 (1956).

9) No deuterium exchange of $AcrD_2$ has ocurred in the presence of $HClO_4$.

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