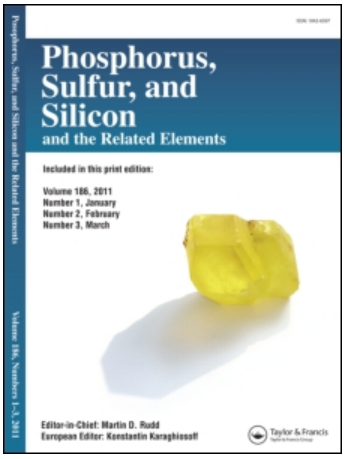

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KINETIC STUDIES ON THE ACID-CATALYZED PUMMERER REACTION OF α-(METHYLSULFINY)ACETOPHENONES

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KINETIC STUDIES ON THE ACID-CATALYZED PUMMERER REACTION OF α-(METHYLSULFINYL)ACETOPHENONES†

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The kinetic behavior of the acid-catalyzed Pummerer reaction of α-(methylsulfinyl)acetophenones in dilute hydrochloric acid has been studied in detail. The kinetic data were analyzed in the light of correlations between the reaction rates and acidity functions, activation parameters, solvent isotope effects, polar effects of substituents, etc. Moreover, ^{18}O-tracer experiments were also carried out using acid media containing $H_2{}^{18}O$. Based on these observations, a plausible mechanism for this reaction has been discussed.

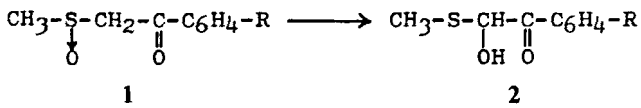
INTRODUCTION

In the last decades, Pummerer reactions have been extensively investigated with keen interest in an effort to make use of the unique nature of this reaction in organic syntheses.[1] Previously, Russell *et al.* have reported that β-keto sulfoxides, which have an acidic methylene group, readily undergo the acid-catalyzed Pummerer reaction under mild conditions, affording the corresponding hemimercaptals of glyoxals in satisfactory yields.[2] During the course of our research concerned with the stereochemistry of β-keto sulfoxides,[3] we considered that the acid-catalyzed Pummerer reaction of optically active β-keto sulfoxides might provide the corresponding optically active hemimercaptals of glyoxals, supposing the reaction may take place through the intramolecular transformation of the hydroxyl group. However, attempts to synthesize optically active hemimercaptals of glyoxals by this method were unsuccessful.[4] This finding has allowed us to attempt kinetic investigations of the acid-catalyzed Pummerer reaction of β-keto sulfoxides in order to clarify the mechanistic features of the reaction in more detail. We have now compiled substantial amounts of kinetic data on the reaction of substituted α-(methylsulfinyl)-acetophenones (**1**) in dilute hydrochloric acid (1.40–3.46 M) and hence wish to advance a plausible mechanism for the reaction.

† Part of this work was presented as a preliminary communication: N. Kunieda, Y. Fujiwara and M. Kinoshita, 37th Annual Meeting of the Chemical Society of Japan, April 1978, Abstr. No. 3B40.

RESULTS AND DISCUSSION

The α-(methylsulfinyl)acetophenones (**1a–1f**) were prepared by treating methylsulfinyl carbanion with the corresponding meta- or para-substituted ethyl benzoate according to the method developed by Russell *et al.*[2a,2c] and by Corey *et al.*[5] Careful kinetic experiments were conducted on the rates of the acid-catalyzed Pummerer reaction in hydrochloric acid of various concentrations ranging from 1.40 M to 3.46 M using a UV spectrophotometric method. Further, under the present reaction conditions, **1** was found to afford the corresponding methyl hemimercaptal of glyoxal (**2**) almost quantitatively, in a fashion analogous to the reaction reported by Russell *et al.*[2a,2c]



1 **2**

1 and **2**

a: R = *p*-CH_3O **d**: R = H

b: R = *p*-CH_3 **e**: R = *p*-Cl

c: R = *m*-CH_3 **f**: R = *m*-Cl

The reaction followed pseudo-first-order kinetics and the rates increased with increase of the acid concentration (see Experimental).

The dependence of the rates of **1d** was first evaluated on the acidity of the media, i.e., the slopes obtained by plotting $\log k_{obs}$ *vs.* $\log[H^+]$ or H_A,[6] the Bunnett *w*-value[7] obtained by plotting $(\log k_{obs} + H_A)$ *vs.* $\log a_{H_2O}$, and the Bunnett–Olsen φ-parameter[8] obtained by plotting $(\log k_{obs} + H_0)$ *vs.* $(H_0 + \log[H^+])$. Previously, it was found by Landini *et al.*[9] and by us[10] that the H_A function developed by Yates *et al.*[11,19] satisfactorily represented the protonation behaviors of sulfoxides. Therefore, we have used the H_A function for the present treatments.

As shown in Figure 1, the plot of $\log k_{obs}$ values† for **1d** were found to be linear with $\log[H^+]$, and the slope was nearly one (0.92, correlation coefficient r = 0.996), whereas the slope of the plots of $\log k_{obs}$ values *vs.* H_A did not become unity (slope = 0.46).

Next we determined that the Bunnett *w*-value for **1d** was 6.70 (r = 0.995), as shown in Figure 2. This value can be classified strictly into the class $w > 3.3$ of the criterion, and it thereby indicates that the reaction proceeds through a route in which water participates as the proton-transfer agent in the rate-determining step.[7] Furthermore, the plot of $(\log k_{obs} + H_0)$ against $(H_0 + \log[H^+])$, illustrated in Figure 3, gave a linear slope. The φ value for **1d** was 1.10 (r = 0.997). According to

†Considering the pK_{BH^+} values of dimethyl sulfoxide and aryl methyl sulfoxides,[9,13] α-(methylsulfinyl)acetophenones (**1**) are assumed to be protonated almost completely. Consequently, the rate constant (k_1) as a function of protonated **1** ($CH_3—{}^+S(—OH)—CH_2—CO—C_6H_4—R$), which is calculated by the equation $(k_1 = k_{obs}(h_0^m + K_{SH^+})/h_0^m)$[13b,14] is useful. However, the pK_{BH^+} value of **1d** has not yet been determined. We have, therefore, used the k_{obs} value without correction in this paper.

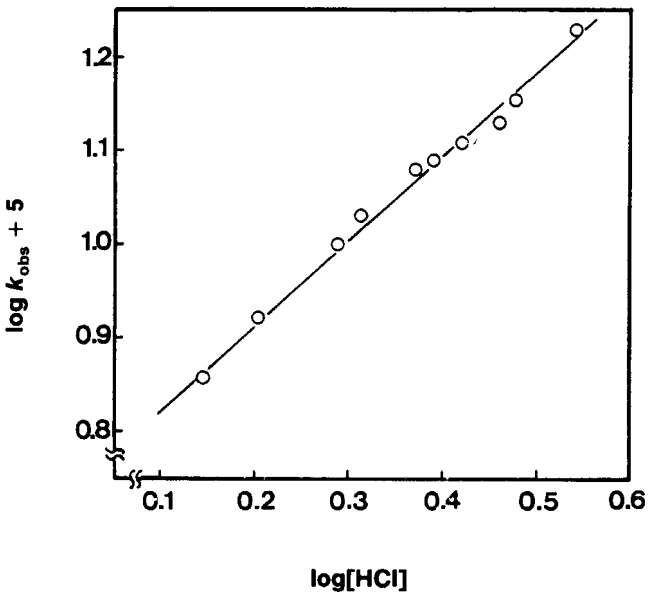


FIGURE 1 The rate constants for **1d** plotted against log[HCl]. **1d** = 6.00×10^{-5} M, at 25°C.

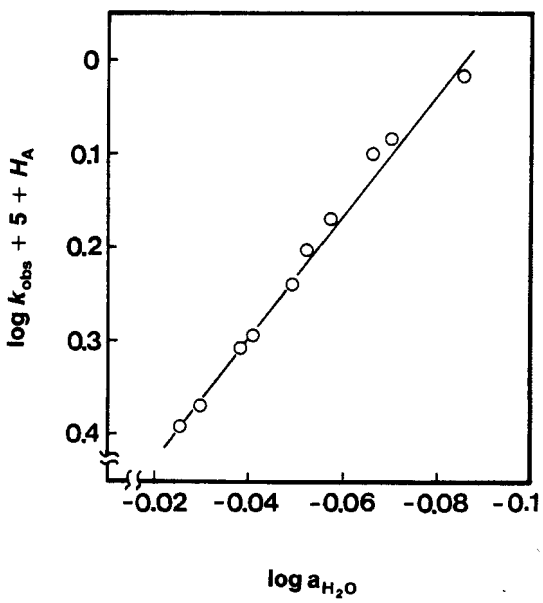


FIGURE 2 Bunnett plots for the reaction of **1d**. **1d** = 6.00×10^{-5} M, at 25°C.

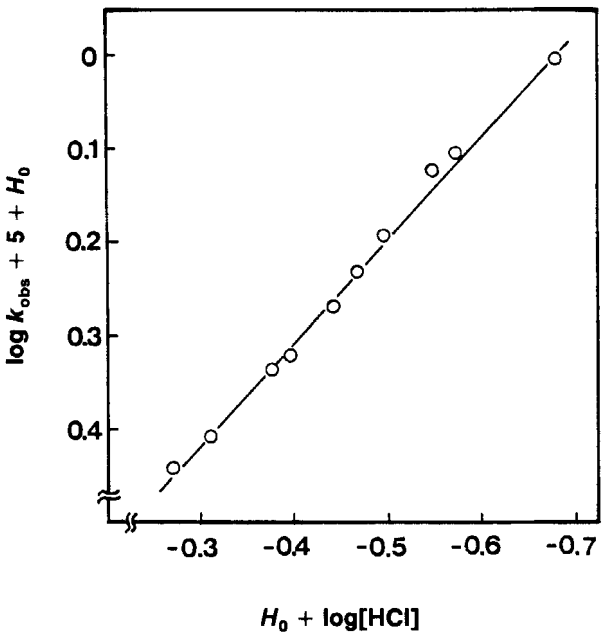


FIGURE 3 The free-energy relationship for the reaction of **1d**. **1d** = 6.00×10^{-5} M, at 25°C.

the Bunnett–Olsen free-energy relationship,[8] this value corresponds to the class $\phi > 0.56$ for water acting as the proton-transfer agent.

The dependence of the rates on the acidities of the acid media (i.e., large w and ϕ values) shows that the reaction proceeds through a route in which water acts as the proton-transfer agent in the rate-determining step. In order to confirm these mechanistic inferences, we also observed the solvent isotope effect for the reaction. Initially, we conducted the kinetics using **1d** and **1d–d** (CH_3—SO—CD_2—CO—C_6H_5) in HCl—H_2O media in order to determine the role of water in regard to the active α-hydrogen of **1d** in the rate-determining step. It is noteworthy that the rate for **1d** was found to be exactly equal to that for **1d–d** (see Table I). This fact seems to suggest that, in this case, the rate of the H—D exchange reaction arising from the acid-catalyzed keto–enol equilibrium is much faster than

TABLE I

Solvent isotope effect of deuteriohydrochloric acid on the reaction rate[a]

Starting **1**	Acid medium[b]	$k_{obs} \times 10^5$ (sec^{-1})	k_{H_2O}/k_{D_2O}
1d	DCl—D_2O	9.06 ± 0.22	
1d	HCl—H_2O	25.6 ± 0.7	2.8
1d–d[c]	DCl—D_2O	9.15 ± 0.39	
1d–d[c]	HCl—H_2O	25.0 ± 0.8	

[a]**1**; 6.28×10^{-5} M, at 30°C.
[b]Acid concentration; 2.33 M.
[c]CH_3—SO—CD_2—CO—C_6H_5.

that of the Pummerer reaction of **1d**. Specifically, the rapid enolization step might well precede the rate-determining step of the reaction. We accordingly observed the solvent isotope effect for the reactions of **1d** in ordinary HCl—H_2O media and **1d–d** in DCl—D_2O media. The value of the ratio of the rate (k_{H_2O}/k_{D_2O}), i.e., the ratio of the rate **1d–d** in DCl—D_2O media to that of **1d** in HCl—H_2O media, is listed in Table I. By considering the fact that the nucleophilicity of D_2O is larger than that of H_2O,[15] the solvent isotope effect observed ($k_{H_2O}/k_{D_2O} = 2.8$) is rather large.

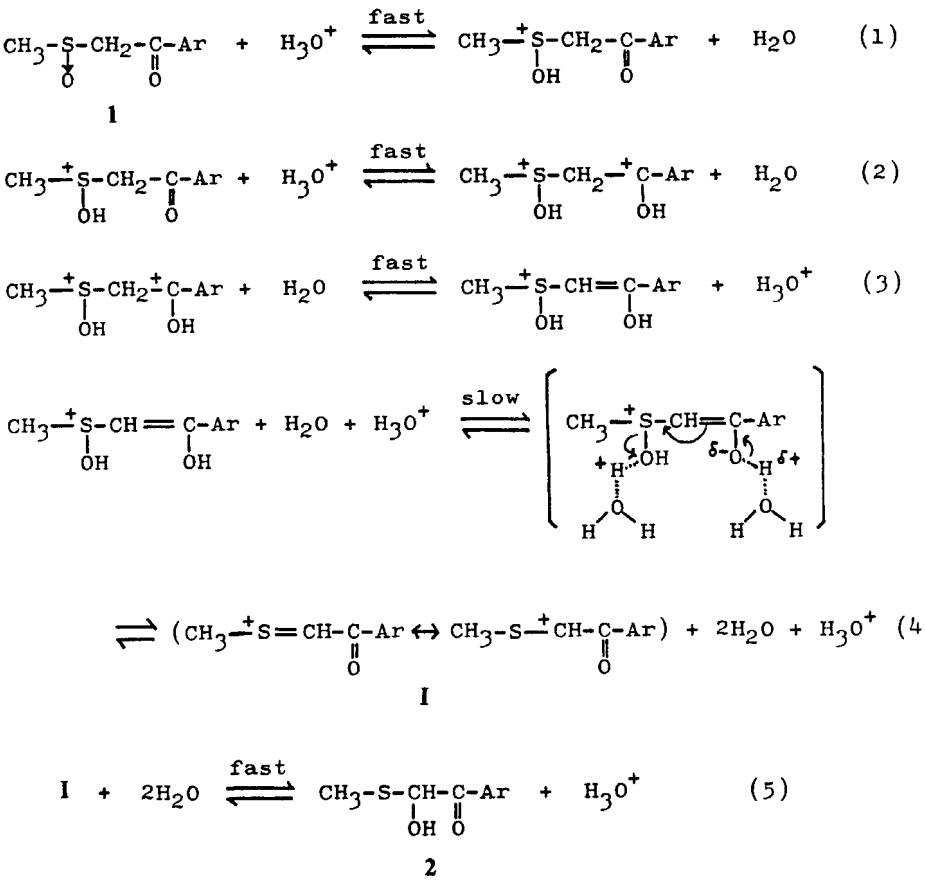
Since it has been known that sulfoxides are practically completely protonated in acid media of moderate concentration,[9,10,13] α-(methylsulfinyl)acetophenones are considered to be protonated almost completely in the range of hydrochloric acid used here [CH_3—$^+$S(—OH)—CH_2—CO—C_6H_4—R].

On the basis of these findings, as well as the results reported by Russell *et al.*,[2] a plausible mechanism, which includes the rate-determining proton transfer by water, may be illustrated by Scheme 1. In this reaction, the enolization and the Pummerer reaction are considered to take place competitively. That is, the initial step of the reaction begins with the rapid protonation equilibrium (Eq. 2), followed by the enolization step (Eq. 3) and then the subsequent rate-determining step to form an intermediate (**I**) (Eq. 4). Equation 5 shows a rapid nucleophilic attack of water on the α-carbon atom of **I** to produce **2**.

Generally, the acid-catalyzed enolization of ketones is considered to proceed through rapid protonation at the carbonyl oxygen and then slow proton transfer of the α-hydrogen to water.[12] Of course, in this reaction, the path 3 may be the rate-determining step for the enolization of **1**, in a fashion analogous to the case of ordinary ketones. However, the acidity of β-keto sulfoxides is known to be much stronger than that of ordinary ketones,[16] and actually the H—D exchange reaction of **1** is very fast as described above. Therefore, we tentatively conclude that the enolization path (Eq. 3) may be regarded as a much faster step in comparison with the rate-determining path (Eq. 4), although further kinetic investigation is necessary to obtain detailed mechanistic evidence for the enolization of **1**. The rate-determining step (Eq. 4) involving the proton transfer of the enol hydrogen to water and the protonation at the sulfoxide oxygen to produce the intermediate **I** is quite reasonable, on the basis of the linear relationship between $\log k_{obs}$ *vs.* $\log[H^+]$, the large *w*-value and φ-parameter, and the large solvent isotope effect. The intermediate **I** resembles in part the intermediate proposed for the rearrangement of pyrimidothiazine-5-oxide.[18]

The energies and entropies of activation, E_a and $\Delta S^{\ddagger}$, were estimated for the reactions of **1d** in 2.47 M acid and in 2.88 M acid. The E_a values were 21.4 kcal/mol (in 2.47 M acid) and 21.5 kcal/mol (in 2.88 M acid), and the $\Delta S^{\ddagger}$ values were −6.6 e.u. (in 2.47 M acid, 25°C) and −6.1 e.u. (in 2.88 M acid, 25°C).

Figure 4 illustrates the polar effects of substituents on the rates for the reactions of a series of substituted α-(methylsulfinyl)acetophenones (**1a–f**). The electron-withdrawing substituents on the aromatic ring increase the reaction rate, and $\log k_R/k_H$ values are nicely correlated with Hammett's σ-values and give a positive ρ-value ($\rho = +0.22$). The activation parameters and the positive ρ-value are consistent with the mechanism involving the rate-determining route of Eq. 4. Finally, when the reaction proceeds through the pathway of Eqs. 1–5, the oxygen of water will be incorporated into **2** *via* path 5. In order to provide evidence as to the



SCHEME 1

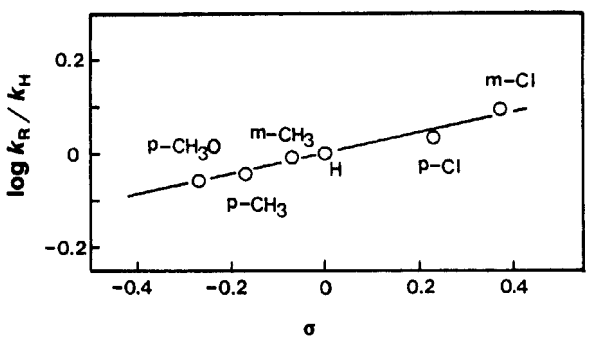


FIGURE 4 The effect of substituents on the rate of the reaction of **1a–f**. **1** = 6.00×10^{-5} M, [HCl] = 2.47 M, at 25°C.

incorporation of oxygen, ^{18}O-tracer experiments were carried out using acid media containing $H_2{}^{18}O$ (1.50 atom%-^{18}O). When **1d** was treated in an acid medium, 2.0 N HCl—$H_2{}^{18}O$/dioxane, for 10 h, the ^{18}O-concentration of **2d** obtained was 1.16 atom%-^{18}O. Assuming that the ^{18}O atom is incorporated only in the hydroxyl group of **2d** from $H_2{}^{18}O$, the ^{18}O-concentration observed is slightly large (the value for 100%-incorporation can be calculated to be 0.85 atom%-^{18}O; see Experimental). This is attributed to the fact that the incorporation of ^{18}O into the starting **1d** and/or the resulting **2d** takes place competitively during the reaction. Actually, ketones, alcohols,[17a] and sulfoxides[17b] are known to undergo the oxygen-exchange reaction in acid media. When **1d** was treated in HCl—$H_2{}^{18}O$/dioxane for 2 h, the ^{18}O-concentration of **1d** recovered was 0.33 atom%-^{18}O. However, when **2d** was treated in HCl—$H_2{}^{18}O$/dioxane for 5 h, the recovered **2d** contained 0.40 atom%-^{18}O (see Experimental). From the results of these control experiments, most of the ^{18}O-content of **2d** is considered to be derived by the incorporation of ^{18}O into the hydroxyl oxygen from $H_2{}^{18}O$ *via* path 5.

In summary, based on these observations, the mechanism shown in Scheme 1 in which water acts as the proton-transfer agent in the rate-determining step is most plausible for the acid-catalyzed Pummerer reaction of **1** in hydrochloric acid.

EXPERIMENTAL

General. The UV spectra were measured with a Jasco UVIDEC 2 type spectrophotometer. The NMR spectra were determined with a Hitachi-Perkin-Elmer R20 or Jeol PS-100 spectrometer; the chemical shifts are reported in δ units, using tetramethylsilane as the internal reference. The melting points were taken in a Yanako MP apparatus and are uncorrected.

Materials

Substituted α-(methylsulfinyl)acetophenones (**1a–f**) were prepared by treating meta- or para-substituted ethyl benzoates with methylsulfinyl carbanion in dry tetrahydrofuran (THF), according to the published method.[2a,2c,5] Satisfactory NMR and elemental analytical data were obtained for all the resulting α-(methylsulfinyl)acetophenones as follows:

1a (R = *p*-CH_3O); mp 103°C (lit,[2c] 101–102°C). NMR ($CDCl_3$): δ 2.78 (s, 3 H, CH_3), 4.39 (q, J = 14 Hz, 2 H, —CH_2—), 3.92 (s, 3 H, —OCH_3), 7.52 (q, 4 H, aromatic). Anal. Found: C, 56.36; H, 5.42%. Calcd for $C_{10}H_{12}SO_3$: C, 56.58; H, 5.70%.

1b (R = *p*-CH_3); mp 107°C (lit,[2c] 106–107°C). NMR ($CDCl_3$): δ 2.50 (s, 3 H, *p*-CH_3), 2.82 (s, 3 H, CH_3), 4.45 (q, J = 14 Hz, 2 H, —CH_2—), 7.47–8.05 (m, 4 H, aromatic). Anal. Found: C, 61.00; H, 6.10%. Calcd for $C_{10}H_{12}SO_2$: C, 61.20; H, 6.16%.

1c (R = *m*-CH_3); mp 68.5°C. NMR ($CDCl_3$): δ 2.42 (s, 3 H, *m*-CH_3), 2.76 (s, 3 H, CH_3), 4.39 (q, J = 14 Hz, 2 H, —CH_2—), 7.37–7.81 (m, 4 H, aromatic). Anal. Found: C, 61.10; H, 5.85%. Calcd for $C_{10}H_{12}SO_2$: C, 61.20; H, 6.16%.

1d (R = H) mp 86°C (lit,[2c] 85–86°C). NMR ($CDCl_3$): δ 2.83 (s, 3 H, CH_3), 4.46 (q, J = 14 Hz, 2 H, —CH_2—), 7.50–8.25 (m, 5 H, aromatic). Anal. Found: C, 59.20; H, 5.43%. Calcd for $C_9H_{10}SO_2$: C, 59.32; H, 5.53%.

1e (R = *p*-Cl); mp 118°C. NMR ($CDCl_3$): δ 2.81 (s, 3 H, CH_3), 4.41 (q, J = 18 Hz, 2 H, —CH_2—), 7.77 (q, 4 H, aromatic). Anal. Found: C, 49.60; H, 4.00%. Calcd for $C_9H_9SO_2Cl$: C, 49.89; H, 4.19%.

1f (R = *m*-Cl); mp 98°C. NMR ($CDCl_3$): δ 2.80 (s, 3 H, CH_3), 4.40 (s, 2 H, —CH_2—), 7.50–8.02 (m, 4 H, aromatic). Anal. Found: C, 49.70; H, 4.13%. Calcd for $C_9H_9SO_2Cl$: C, 49.89; H, 4.19%.

Deuterio-α-(methylsulfinyl)acetophenone (CH_3—SO—CD_2—CO—C_6H_5)(**1d-d**) was prepared according to the following procedure. A 50 ml round-bottomed flask containing a magnetic stirring bar was equipped with a rubber septum and a nitrogen inlet tube. After flushing with dry nitrogen, 10 ml of dry THF, **1d** (1 mmol), and 1 ml of 1 mmol/ml solution of ethylmagnesium bromide in ether were injected successively through the septum *via* syringe into the flask at 0°C, and the solution was stirred for 15 min. D_2O (2 ml) was then added *via* syringe to the solution. The reaction mixture was extracted with

chloroform (3 × 30 ml). The chloroform layer was dried (Na_2SO_4) and evaporated under a vacuum. The recrystallization of the crude product from ethyl acetate yielded the corresponding analytically pure **1d–d** in a 60% yield; mp 86°C. NMR ($CDCl_3$): δ 2.80 (s, 3 H, CH_3), 7.50–8.20 (m, 5 H, aromatic).

Hydrochloric acid. The concentration was determined by titration with a standard alkali solution. The H_A values of the media were obtained by interpolation from a graph of the data of Yates *et al.*[19] The H_0 values used here are the data evaluated by Paul and Long.[6a] DCl—D_2O solutions were prepared from MERCK DCl (min. 99%-d) by dilution with D_2O (min. 99.75%-d). The activity of water, $\log a_{H_2O}$, of the acid media was the value interpolated from the table of Bunnett.[20]

Product Analysis and Kinetic Procedures. A solution of **1d** (6.0×10^{-3}M) (prepared from 1 ml of a 27.3 mg/ml solution of **1d** in ethanol and 24 ml of 2.33 M hydrochloric acid) was stirred for 24 h at 30°C. The reaction mixture was extracted with chloroform (3 × 30 ml), and the chloroform layer was dried (Na_2SO_4) and evaporated *in vacuo*. The NMR spectrum ($CDCl_3$) of the resulting product exhibited signals at 2.00, 4.36, and 6.14 ppm due to —SCH_3, —OH, and —CH— protons of methyl hemimercaptal of phenylglyoxal (**2d**), respectively. The formation of by-products, such as thiophenol and phenylglyoxal, was not detected.[2c]

Kinetic experiments were carried out with a UV spectrophotometer with a thermostated cell compartment. Reactions were followed by continuous observation of the decrease in absorbance at the following wavelengths: **1a**, 280 nm; **1b**, 253 nm; **1c**, 253 nm; **1d**, 253 nm; **1e**, 246 nm; **1f**, 253 nm. In the typical procedure, 0.16 ml of an 1.5×10^{-3}M stock solution of **1d** in ethanol was added to 3.84 ml of hydrochloric acid contained in 1 cm UV cell at a preset temperature and the rate was measured directly by checking the decrease in absorbance, A, at 253 nm. The pseudo-first-order rate constant, k_{obs}, was evaluated by the following equation, $k_{obs}t = \ln(A_0 - A_\infty)/(A_t - A_\infty)$, where A_0, A_t, and A_∞ are the absorbances at time 0, t, and after 12–16 half-times, respectively. The first-order kinetic plots were linear over at least one half-life, with an error of 3–5 percent. Kinetic runs were done at least 3 times, and each run had 10–15 data points. The typical plots are illustrated in Figure 5. Activation parameters were calculated by least-squares analysis of the Arrhenius plots (see Figure 6).

^{18}O-Tracer Experiments. A solution of 360 mg of **1d** in a mixture of 2.0 N HCl—$H_2{}^{18}O$ (1.2 ml) and dioxane (2 ml) was stirred at 25°C for 10 h. After the usual work up, the resulting analytically pure **2d** was subjected to the ^{18}O analysis using a mass spectrometer. The ^{18}O-atom% was calculated from the mass peak heights 44 and 46 of carbon dioxide according to the method described by Samuel (natural CO_2 = 0.20 atom%-^{18}O).[21] The HCl—$H_2{}^{18}O$ media contained 1.50 atom%-^{18}O (excess ^{18}O-content =

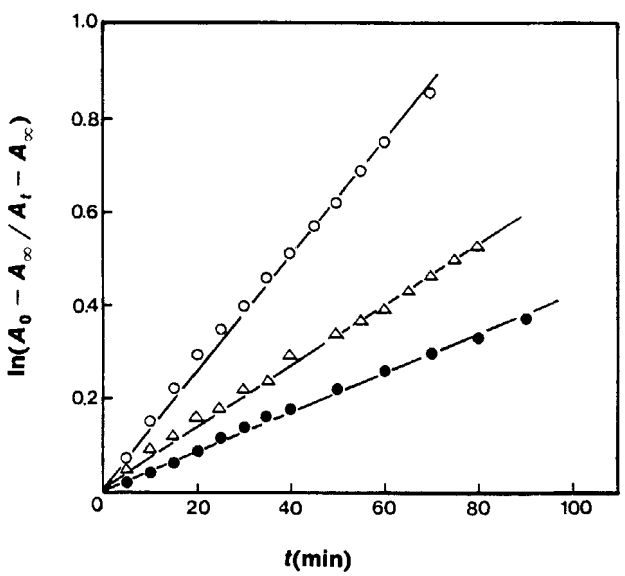


FIGURE 5 Typical first-order kinetic plots for the reaction of **1d**. **1d** = 6.00×10^{-5} M. ●: in 1.40 M acid at 25°C; △: in 2.47 M acid at 25°C; ○: in 2.88 M acid at 30°C.

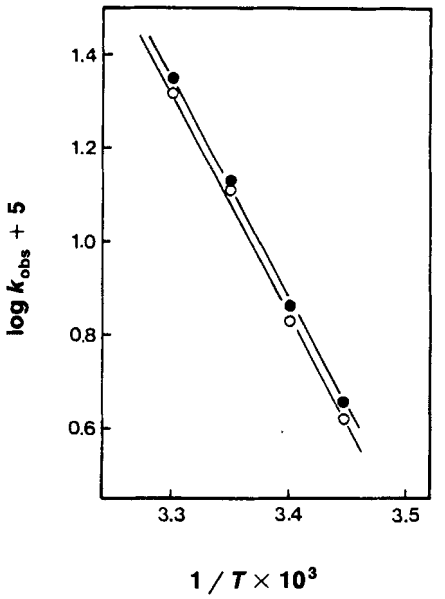


FIGURE 6 Arrhenius plots for the reaction of **1d**. ○ : in 2.47 M acid; ● : in 2.88 M acid.

1.30 atom%), and the ^{18}O-concentration of **2d** obtained was 1.16 atom%-^{18}O (excess ^{18}O-content = 0.96 atom%).

When **1d** (360 mg) was treated in the same acid medium described above for 2 h at 25°C, **1d** (70 mg) was recovered after the usual work up and preparative TLC on silica gel. The ^{18}O-concentration of **1d** recovered was 0.33 atom%-^{18}O (excess ^{18}O-content = 0.13 atom%). When **2d** (175 mg) was treated in a mixture of 2.0 N HCl—$H_2{}^{18}O$ (1.2 ml) and dioxane (4 ml) for 5 h at 25°C, **2d** (120 mg) was recovered after the usual work up. The ^{18}O-concentration of **2d** recovered was 0.40 atom%-^{18}O (excess ^{18}O-content = 0.20 atom%).

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REFERENCES

1. For reviews see: G. A. Russell and G. J. Mikol, "Acid-Catalyzed Rearrangements of Sulfoxides and Amine Oxides. The Pummerer and Polonovski Reactions," in "Mechanisms of Molecular Migrations," ed. by B. S. Thyagarajan, John Wiley & Sons, New York (1968), Vol. 1, p. 157; T. Durst, *Advances in Organic Chemistry*, **6**, 285 (1969); S. Oae, "Sulfoxides and Sulfilimines," in "Organic Chemistry of Sulfur," ed. by S. Oae, Plenum Press, New York (1977), p. 406; T. Numata and S. Oae, *Yuki Gosei Kagaku Kyokai Shi*, **35**, 726 (1977); T. Numata, *ibid.*, **36**, 845 (1978); S. Oae and T. Numata, "The Pummerer and Pummerer Type Reactions," in "Isotopes in Organic Chemistry," ed. by E. Buncel and C. C. Lee, Elsevier Pub. Co., Amsterdam (1980), Vol. 5, Chap. 2.
2. (a) H.-D. Becker, G. J. Mikol and G. A. Russell, *J. Am. Chem. Soc.*, **85**, 3410 (1963); (b) H.-D. Becker and G. A. Russell, *J. Org. Chem.*, **28**, 1896 (1963); (c) G. A. Russell and G. J. Mikol, *J. Am. Chem. Soc.*, **88**, 5498 (1966).
3. (a) N. Kunieda, J. Nokami and M. Kinoshita, *Chem. Lett.*, **1974**, 369; (b) J. Nokami, N. Kunieda and M. Kinoshita, *ibid.*, **1977**, 249; (c) N. Kunieda, H. Motoki and M. Kinoshita, *ibid.*, **1978**, 713; (d) N. Kunieda and M. Kinoshita, *Phosphorus and Sulfur*, **10**, 383 (1981); (e) N. Kunieda, A. Suzuki and M. Kinoshita, *Bull. Chem. Soc. Jap.*, **54**, 1143 (1981).

4. N. Kunieda and M. Kinoshita, unpublished data.
5. E. J. Corey and M. Chaykovsky, *J. Am. Chem. Soc.*, **87**, 1345 (1965).
6. (a) M. A. Paul and F. A. Long, *Chem. Revs.*, **57**, 1, 935 (1957); (b) L. Zucker and L. P. Hammett, *J. Am. Chem. Soc.*, **61**, 2791 (1939); (c) C. H. Rochester, "Acidity Functions," Academic Press, New York (1970).
7. J. F. Bunnett, *J. Am. Chem. Soc.*, **82**, 499 (1960); **83**, 4956, 4968, 4973, 4978 (1961).
8. J. F. Bunnett and F. P. Olsen, *Can. J. Chem.*, **44**, 1899 (1966); *ibid.*, **44**, 1917 (1966).
9. (a) D. Landini, G. Modena, G. Scorrano and F. Taddei, *J. Am. Chem. Soc.*, **91**, 6704 (1969); (b) D. Landini, G. Modena, F. Montanari and G. Scorrano, *ibid.*, **92**, 7168 (1970).
10. (a) N. Kunieda and S. Oae, *Bull. Chem. Soc. Jpn.*, **46**, 1745 (1973); (b) N. Kunieda, T. Numata and S. Oae, *Phosphorus and Sulfur*, **3**, 1 (1977).
11. K. Yates, J. B. Stevens and A. R. Katritzky, *Can. J. Chem.*, **42**, 1957 (1964).
12. For example see: C. K. Ingold, "Structure and Mechanism in Organic Chemistry," second ed, Cornell University Press, Ithaca, N.Y. (1969), Chap. 11; Chap. 5 (pp. 162 and 169) of Ref. 6c.
13. (a) P. Haake and R. D. Cook, *Tetrahedron Lett.*, **1968**, 427; (b) G. Scorrano, *Acc. Chem. Res.*, **6**, 132 (1973).
14. K. Yates, *Acc. Chem. Res.*, **4**, 136 (1971).
15. For example see: E. Högfeldt and J. Bigeleisen, *J. Am. Chem. Soc.*, **82**, 15 (1960); C. F. Bernasconi, D. J. Carré and A. Kanavarioti, *ibid.*, **103**, 4850 (1981); Chap. 2 of Ref. 6c.
16. N. Kunieda, Y. Fujiwara, J. Nokami and M. Kinoshita, *Bull. Chem. Soc. Jpn.*, **49**, 575 (1976).
17. (a) D. Samuel and B. L. Silver, "Oxygen Isotope Exchange Reaction of Organic Compounds," in "Advances in Physical Organic Chemistry," ed. by V. Gold, Academic Press, New York (1965), Vol. 3, p. 123; (b) S. Oae, "Sulfoxides and Sulfilimines," in Organic Chemistry of Sulfur," ed. by S. Oae, Plenum Press, New York (1977), Chap. 8, p. 413.
18. E. F. Schroeder and R. M. Dodson, *J. Am. Chem. Soc.*, **84**, 1904 (1962).
19. K. Yates and J. C. Riordan, *Can. J. Chem.*, **43**, 2328 (1965).
20. J. F. Bunnett, *J. Am. Chem. Soc.*, **83**, 4956 (1961).
21. D. Samuel, "Methodology by Oxygen Isotope," in "Oxygenases," ed. by O. Hayaishi, Academic Press, New York (1962), Chap. 2.