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SHORT COMMUNICATIONS

GENERAL BASE CATALYSIS OF PHOTO-SMILES REARRANGEMENT OF 1-(4-NITROPHENOXY)-2-ANILINOETHANE IN AQUEOUS SOLUTION. IDENTITY OF THE PROTON-DONATING INTERMEDIATE

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ABSTRACT

$4\text{-}O_2NC_6H_4OCH_2CH_2NHPh$ undergoes clean base-catalyzed Smiles photorearrangement to $4\text{-}O_2NC_6H_4N(Ph)CH_2CH_2OH$ in dimethyl sulfoxide–water (25 : 75). A linear plot of ϕ^{-1} vs $[OH^-]^{-1}$ indicated that the limiting quantum yield at high $[OH^-]$ is 0·12 and that uncatalyzed photorearrangement does not occur. Rate constants for the deprotonation step were determined for a variety of bases having conjugate acid pK_a values in the range 5–10. When plotted according to the Brønsted Catalysis Law, these data gave a non-linear plot approaching slopes of zero and unity above and below a pK_a of 6–7. This indicates that the proton-donating intermediate in this photo-Smiles rearrangement is the zwitterion diradical ($pK_a \approx 7$) rather than the Meisenheimer complex ($pK_a \approx 2$).

INTRODUCTION

Photo-Smiles rearrangements in acetonitrile of $4\text{-}O_2NC_6H_4\text{-}O(CH_2)_nNHPh$[1-3] and related compounds[4-6] are reported to be 'accelerated'[3] in several cases by triethylamine, and to occur through zwitterion diradical and σ-complex intermediates. Our interest in mechanisms of photo-Smiles rearrangements[7,8] and of catalysis in photochemistry[9] raised for us the questions of whether the acceleratory effect of Et_3N was due to base catalysis, whether the base catalysis, if involved, was general or specific, and which intermediate interacted with the base. We report that the photorearrangement of $4\text{-}O_2NC_6H_4OCH_2CH_2NHPh$ (**1**) to $4\text{-}O_2NC_6H_4N(Ph)CH_2CH_2OH$ (**2**) occurs cleanly in aqueous solutions and is subject to general base catalysis[9] involving the zwitterion diradical.

Irradiation of **1** ($5{\cdot}0 \times 10^{-5}$ M) at 313 nm in aqueous acetonitrile (4 : 1 water–acetonitrile) or aqueous dimethyl sulfoxide (DMSO) (3 : 1 water–DMSO) at a measured pH of 11·00 in the presence of NaOAc, pyridines or alkylamines caused clean conversion to **2**. This conclusion is based on the similarity of the final electronic spectrum to that reported for **2** in acetonitrile,[2]

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and the occurrence of isobestic points at 353, 273 and 252 nm in successive spectra of the reaction solutions. (The same isobestic points were found for the thermal, second stage of a desulfonative double Smiles rearrangement in 0·1–1 M aqueous NaOH at 61 °C.[10]) Smiles rearrangement of **1** did not occur in the dark even when it was heated at 70 °C in aqueous 0·1 M K_2PHO_4 for 2 weeks.

Reaction solution for quantum yield determinations ($5\cdot0 \times 10^{-5}$ M in **1**) were prepared under nitrogen in aqueous DMSO (3 : 1 water–DMSO). NaOH solutions were prepared by dilution. Constant NaOH concentration in the presence of a weak base was obtained by adjustment to a constant pH meter reading that corresponded to [NaOH] = $2\cdot78 \times 10^{-4}$ M. The ionic strength was adjusted with KCl to $\mu = 0.10$. Irradiations were conducted in cuvettes at 25 °C with 313 nm light, and light intensities for each run were monitored with Aberchrome 540 in toluene[11] as actinometer. Progress of the reactions was monitored by measuring the decrease in absorbance at 313 nm ($\varepsilon_{\text{reactant}} = 11\,420$; $\varepsilon_{\text{product}} = 1600$).

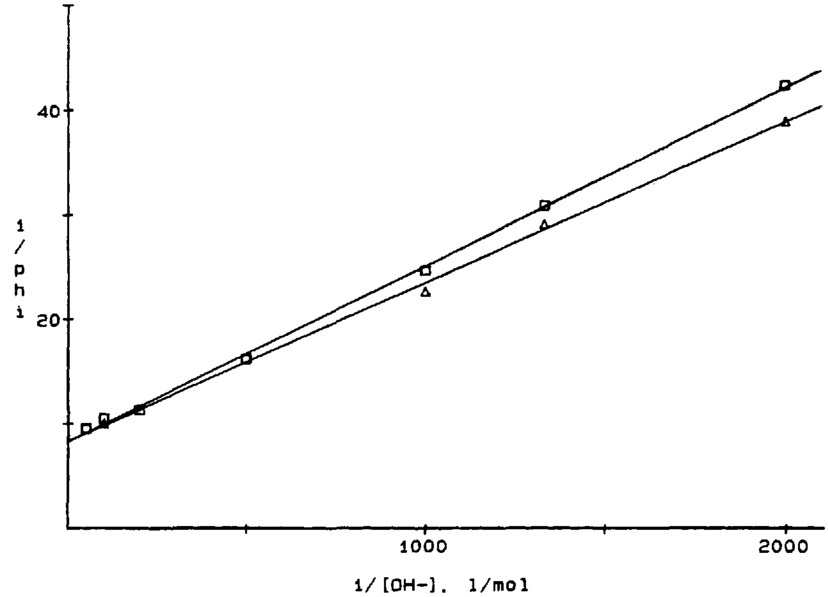


Figure 1. Dependence of efficiency of photo-Smiles rearrangement of **1** on the hydroxide ion concentration. □, Uncontrolled ionic strength; △, ionic strength = 0·10

Table 1. Quantum yields and rate constants for general base catalysts[a]

Base	Concentration (M)	ϕ_{Smiles}	k_S[b] ($\text{l mol}^{-1}\text{s}^{-1}$)	pK_a[c] (25 °C)
OH^-	$2\cdot78 \times 10^{-4}$	0·016	($1\cdot4 \times 10^{10}$)	15·7
OAc^-	0·100	0·027	$3\cdot6 \times 10^{7}$	4·75
Pyridine	0·100	0·041	$9\cdot5 \times 10^{7}$	5·17
4-Picoline	0·100	0·059	$2\cdot1 \times 10^{8}$	6·00
2, 4, 6-Collidine	0·100	0·065	$2\cdot6 \times 10^{8}$	7·43
Glycinamide	0·100	0·080	$4\cdot7 \times 10^{8}$	8·03
Ethanolamine	0·100	0·095	$9\cdot3 \times 10^{8}$	9·50

[a] All reaction solutions are 3 : 1 water–DMSO containing $2\cdot78 \times 10^{-4}$ M OH^- at 0·1 ionic strength at 25 °C.
[b] Rate constants are based on $k_{S(OH)} = 1\cdot4 \times 10^{10}\ \text{l mol}^{-1}\text{s}^{-1}$.[13]
[c] pK_as for aqueous solution from Reference 14.

Figure 1 shows that reciprocal quantum yield is linearly dependent on $[OH^-]^{-1}$. This means that the photorearrangement is catalyzed by hydroxide ion in the first order; the absence of a plateau region at low $[OH^-]$ implies that uncatalyzed photorearrangement virtually does not occur. The intercepts of the plots for uncontrolled and 0·1 ionic strength are the same (8·27), which indicates a limiting quantum yield of 0·12.

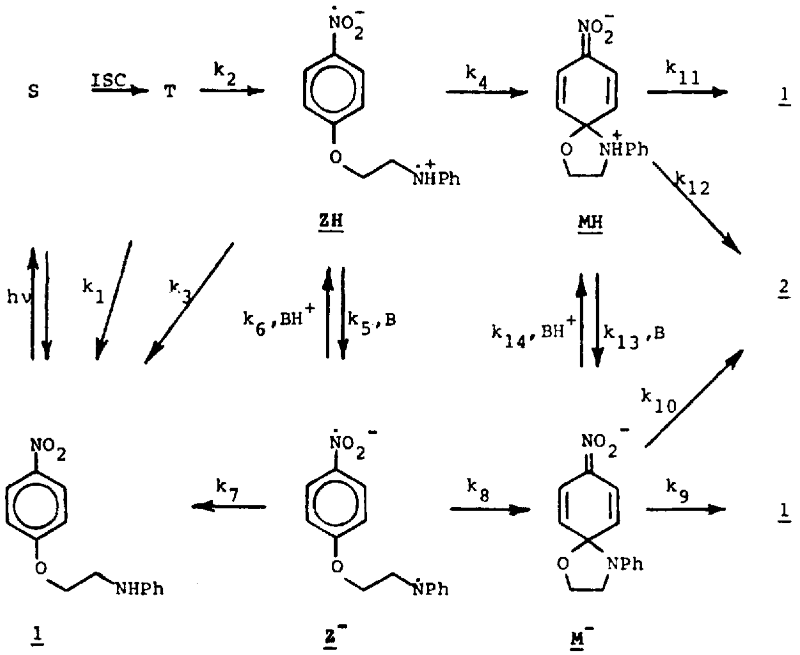
NaOAc and five amine bases at constant pH and ionic strength were found to increase the efficiency of photorearrangement, as shown in Table 1. (Aqueous pK_a values are used because 25% DMSO affects the pK_as, especially of the amines, only slightly.[12]) This indicates that the reaction is subject to general base catalysis.

For the mechanism shown in Scheme 1, involving deprotonation of the zwitterion diradical (ZH), the reciprocal quantum yield expression is given by equation (1), where $f = [k_8/(k_7 + k_8)] \times [k_{10}/(k_9 + k_{10})]$.

$$\frac{1}{\phi} = \frac{1}{\phi_{\mathrm{ISC}}} \frac{1}{f} \left(1 + \frac{k_1}{k_2}\right)\left(1 + \frac{k_3 + k_4}{\sum_i k_{5,i}[\mathrm{B}_i]}\right) \tag{1}$$

Equation (1) assumes that $k_6[BH^+] \ll k_7 + k_8$, because general base catalysis is observed, and that $k_{12} \ll k_{11}$, because uncatalyzed photorearrangement is very inefficient.

The deprotonation rate constants for the bases in Table 1 were calculated with equation (1) by using the intercept of 8·27 from Figure 1, a rate constant of $1{\cdot}4 \times 10^{10}\ \mathrm{l\,mol^{-1}\,s^{-1}}$ for OH^- in k_5 (the reported rate constant[13] for $^-O_2CCH_2NH_3^+ + OH^-$ is $1{\cdot}4 \times 10^{10}\ \mathrm{l\,mol^{-1}\,s^{-1}}$) and the data for hydroxide (Table 1) to calculate $k_3 + k_4$. The quantum yield at the same OH^- concentration with an additional base present at known concentration was then inserted in equation (1) with the value for $k_3 + k_4$ to obtain the rate constant k_5 for the base. The reproducibility of our quantum yields was better than ± 4% and the cumulative relative error



Scheme 1

in the rate constants obtained was less than 10%. The absolute error is probably larger (± 25%) because of the possibility of contamination by CO_2 at these low OH^- concentrations. The rate data are plotted in Figure 2 according to the Brønsted Catalysis Law [equation (2)].

$$\log k_{\text{cat}} = \beta(\text{p}K_{\text{a}_{\text{BH}}}) + \text{constant} \tag{2}$$

We see no reason to question Mutai and co-workers' flash photolysis evidence[2,3] that the primary event from the triplet state of **1** in acetonitrile is rapid electron transfer to give the zwitterion diradical (ZH). The electron transfer is exceedingly fast in acetonitrile (τ of excited state **1** is less than 1 ns), and it should be more facile in 25% DMSO–water because of the increase in the polarity of the medium (i.e. $k_2 \gg k_1$). We also see no reason to question their assignment of a transient at 420 nm to a σ-complex (M^-) preceding the product. The pathway from ZH to M^- could involve ZH or MH as the proton donor. Mutai and co-workers[2,3] suggested that it may be the zwitterion diradical on the basis that 'intramolecular exciplex or excited state intramolecular charge-transfer interaction may facilitate proton release from the NH group.'

The pK_a of ZH may be estimated to be about 7 in view of the reported pK_a of 7·0 ± 0·1 for the aniline cation radical.[15] The pK_a of MH is less clear, but can be estimated to be 2 ± 1 by applying the rule[16] that the pK_a of a protonated spiro Meisenheimer complex such as MH is about three units less than that of the corresponding alkylanilinium ion ($PhN^+H_2CH_3$ in this case, pK_a = 4·8). The Brønsted plot shows a break at pK_a 6–7 between a rising portion at the left and a plateau at the right. Reaction of ZH with an amine represents an unsymmetrical charge type in which the products of two overall neutral species are an anion and a cation. According to Eigen,[13] the limiting proton transfer rate constant is expected to be $10^9\,\text{l}\,\text{mol}^{-1}\,\text{s}^{-1}$, and this limit is reached at an amine conjugate acid pK_a (Figure 2) of 9·5. The intersection of the ideal lines at $\beta = 0$ and $\beta = 1$ (broken lines in Figure 2) occurs at 6·14 on

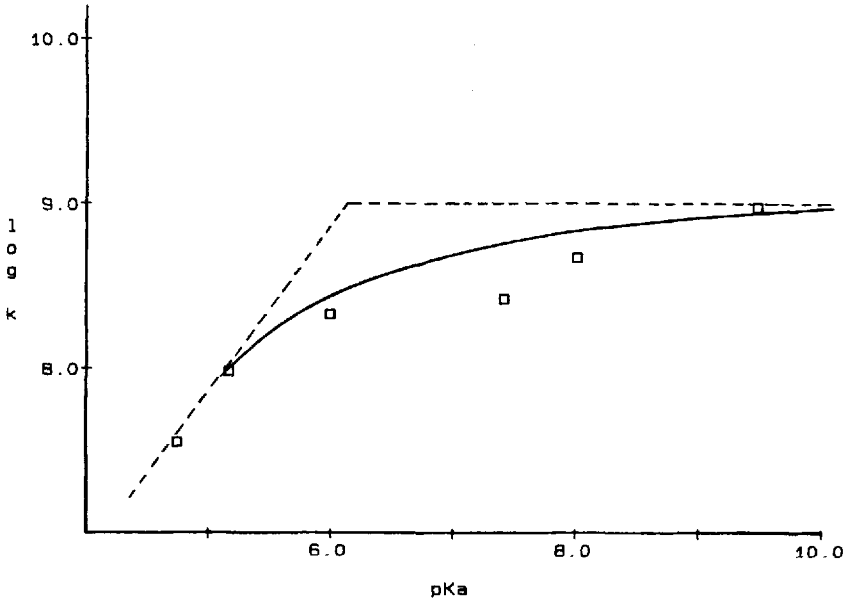


Figure 2. Brønsted Catalysis Law plot of dependence of rate constant of the deprotonation step on the basicity of the base. Bases (left to right): acetate, pyridine, 4-picoline, 2,4,6-collidine, glycinamide and ethanolamine.

the pK_a scale. This intersection is expected[13] to be displaced from the pK_a of the proton donor by an amount equal to the difference in the logarithms of the diffusion-limited forward and reverse reactions. Since reaction of Z^- with a positively charged proton donor should approach a diffusion rate of ca $10^{10}\,l\,mol^{-1}\,s^{-1}$ because it is a charge recombination,[13] we expect a displacement of the intersection of about one unit along the pK_a scale. The pK_a of the proton donor must therefore be very close to 7. We conclude that ZH is the intermediate and that MH is not.

If ZH is the proton donor, the slope to intercept ratio of Figure 1 ($0{\cdot}0018$ at $\mu = 0{\cdot}1$) corresponds to $(k_3 + k_4)/k_5$ for hydroxide ion as the base. If k_5 is $1{\cdot}4 \times 10^{10}\,l\,mol^{-1}\,s^{-1}$, then $k_3 + k_4 = 2{\cdot}6 \times 10^7\,s^{-1}$. This indicates a lifetime for ZH in the absence of base of 38 ns, which agrees well (perhaps fortuitously) with the lifetime (65 ns) of ZH in acetonitrile observed by flash photolysis.[2] The intercept in Figure 1 ($8{\cdot}27$) corresponds to $(1/\phi_{ISC})(1/f)(1 + k_1/k_2)$. If $\phi_{ISC} = 0{\cdot}7$[17] and $k_2 \gg k_1$,[2] then the partitioning function $f = 0{\cdot}17$. Of the two terms (see above) contributing to f, k_{10} should greatly exceed k_9 because of the much better leaving ability of RO^- compared with $RNPh^-$.[16] This conclusion allows the estimation that $k_8/(k_7 + k_8) = 0{\cdot}17$, i.e. 17% of Z^- couples to form M^- while 83% reverts to **1**.

That MH is likely to be totally incapable of forming M^- can be inferred from results on the thermal chemistry of Meisenheimer complexes. Bernasconi[16] reported that the analog of MH having CH_3 in place of Ph and two additional nitro groups adjacent to the spiro carbon atom expels the amino group at $k = 1{\cdot}2 \times 10^5\,s^{-1}$. Applying the rule[16] that the loss of each *ortho* nitro substituent accelerates the expulsion by a factor of 4×10^4, the loss of two nitro groups would make $k_{11} = 10^{14}\,s^{-1}$. This does not yet correct for the effect of replacing CH_3 with Ph, which would accelerate k_{11} further by a factor of 10^4–10^5. If the value of k_{11} were as low as $10^{11}\,s^{-1}$, $0{\cdot}1$ M base accepting the MH proton at a diffusion rate of $10^9\,l\,mol^{-1}\,s^{-1}$ could capture only $0{\cdot}1$% of the intermediate.

We have reported previously[18] on the α-cyclodextrin inhibition of the photo-Smiles rearrangement of **1**, which yields a Brønsted plot virtually identical with that shown in Figure 2. These appear to be the first examples of Brønsted plots for general base-catalyzed photochemical reactions. Such plots for general acid-catalyzed photoreactions in which the proton is added to a carbon atom (bearing orbitals directly involved in the excitation) yield values of α that are low ($0{\cdot}14$–$0{\cdot}18$),[19] and this fact has been the subject of theoretical study.[20] The current example corresponds closely to the hydrogen-bonding acids and bases model described by Eigen;[13] the slope in the strength-dependent regime becomes unity, and the fast reaction limit approaches the rate of diffusion.

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REFERENCES

1. K. Mutai, S. Kanno and K. Kobayashi, *Tetrahedron Lett.* 1273 (1978).
2. K. Yokoyama, R. Nakagaki, J. Nakamura, K. Mutai and S. Nagakura, *Bull. Chem. Soc. Jpn.* **53**, 2472 (1980).
3. K. Mutai and K. Kobayashi, *Bull. Chem. Soc. Jpn.* **53**, 462 (1981).
4. (a) K. Yokoyama, J. Nakamura, K. Mutai and S. Nagakura, *Bull. Chem. Soc. Jpn.* **55**, 317 (1982); (b) K. Mutai, K. Yokoyama, S. Kanno and K. Kobayashi, *Bull. Chem. Soc. Jpn.* **55**, 1112 (1982).

5. K. Mutai, K. Kobayashi and K. Yokoyama, *Tetrahedron* **40**, 1755 (1984).
6. (a) K. Mutai, R. Nakagaki and H. Tukada, *Bull. Chem. Soc. Jpn.* **58** 2066 (1985); (b) R. Nakagaki, M. Hiramatsu, K. Mutai and S. Nagakura, *Chem. Phys. Lett.* **121**, 262 (1985).
7. (a) G. G. Wubbels, A. M. Halverson and J. D. Oxman, *J. Am. Chem. Soc.* **102**, 4848 (1980); (b) G. G. Wubbels, A. M. Halverson, J. D. Oxman and V. H. De Bruyn, *J. Org. Chem.* **50**, 4499 (1985).
8. G. G. Wubbels and D. W. Celander, *J. Am. Chem. Soc.* **103**, 7669 (1981).
9. G. G. Wubbels, *Acc. Chem. Res.* **16**, 285 (1983); **17**, 234 (1984).
10. A. C. Knipe and J. Lound-Keast, *J. Chem. Soc., Perkin Trans. 2* 1741 (1976).
11. H. G. Heller and J. R. Langan, *J. Chem. Soc., Perkin Trans. 1* 341 (1981).
12. A. K. Covington and T. Dickinson (Eds), *Physical Chemistry of Organic Solvent Systems.* Plenum Press, New York (1973).
13. M. Eigen, *Angew. Chem., Int. Ed. Engl.* **3**, 1 (1964).
14. D. D. Perrin (Ed.), Dissociation Constants of Organic Bases in Aqueous Solutions, Butterworths, London (1965).
15. E. J. Land and G. Porter, *Trans. Faraday Soc.* **59**, 2016 (1963).
16. C. F. Bernasconi, *Acc. Chem. Res.* **11**, 147 (1978).
17. R. Hurley and A. C. Testa, *J. Am. Chem. Soc.* **92**, 1949 (1970).
18. G. G. Wubbels, B. R. Sevetson and S. N. Kaganove, *Tetrahedron Lett.* **27**, 3103 (1986).
19. (a) P. Wan and K. Yates, *J. Org. Chem.* **48**, 869 (1983); (b) J. McEwen and K. Yates, *J. Am. Chem. Soc.* **109**, 5800 (1987).
20 (a) K. Yates, *J. Am. Chem. Soc.* **108**, 6511 (1986); (b) K. Yates, *J. Phys. Org. Chem.* to appear in 1989.