

STUDIES OF THE PHOTOREACTIONS OF HETEROCYCLIC N-DIOXIDES: IDENTIFICATION OF THE OXAZIRIDINE INTERMEDIATE OF QUINOXALINE-1,4-DIOXIDE

HIROKI KAWATA*, KOICHI KIKUCHI and HIROSHI KOKUBUN

Department of Chemistry, Faculty of Science, Tohoku University, Aoba, Aramaki, Sendai 980 (Japan)

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Summary

The photochemical rearrangement of quinoxaline-1,4-dioxide (1) was studied in an aqueous solution. Three types of transient absorption spectrum in addition to the triplet-triplet absorption spectrum were observed by conventional flash photolysis. One transient, designated 2, observed in the neutral solution was assigned to the oxaziridine intermediate. Two transients, designated 5 and 6, were observed in the acidic solution. 5 was tentatively assigned as the protonated form of 2.

1. Introduction

Many photochemical investigations of aromatic amine *N*-oxides have been carried out and it has been suggested that the first step in their photo-induced rearrangement is the formation of the oxaziridine intermediate from the excited singlet state [1]. However, the oxaziridine intermediates of aromatic amine *N*-oxides have not been detected although the nitrones have [2, 3].

The flash photolysis of an aerated aqueous solution of quinoxaline-1,4-dioxide (1) at room temperature revealed a transient absorption in the UV region [4]. Since the transient, designated 2, was found to be the precursor of the photoproduct 2-quinoxalone-4-oxide (3), 2 was tentatively assigned to the oxaziridine (Fig. 1). Tokumura *et al.* [5] have recently reported a transient absorption in the UV region which they assigned to the oxaziridine intermediate of 6-cyanophenanthridine-5-oxide.

In this work the photoinduced rearrangement of 1 was studied in detail by continuous illumination and flash experiments in order to determine whether the transient absorption is due to the oxaziridine.

*Present address: College of Humanities and Social Sciences, Iwate University, Ueda, Morioka 020, Japan.

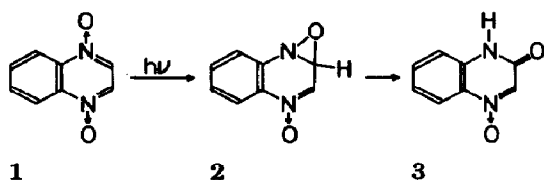


Fig. 1.

2. Experimental details

1 was synthesized according to the method of Bowie and Jones [6] and was recrystallized three times from a water-ethanol mixture. Triphenylphosphine (TP) (Guaranteed Reagent grade, Kanto-Kagaku) was recrystallized from ethanol twice.

The absorption spectra were measured using a Hitachi EPS-3T spectrophotometer. The fluorescence spectra were recorded using a modified Hitachi EPU spectrophotometer. The sample solution was exposed to continuous irradiation at 365 nm. The light source was a Toshiba SHL-100 UV mercury lamp with Hoya U-2 and Toshiba L-1A filters. The quantum yield of the photoreaction was determined using an aerated solution of acridine in ethanol as an actinometer [7]. The recovery of the absorption of 1 after continuous irradiation was measured using a JASCO UVIDEC-2 spectrophotometer. The flash energy was 130 J and the full width at half-maximum was about 10 μ s. A Hoya UVP filter was used for the excitation. The acidity of the sample solution was adjusted by varying the sulphuric acid concentration. The pH of the solution was measured using a Toa HM-18 pH meter. Unless noted otherwise, the sample solutions were not degassed. All the measurements were made at 25 °C unless otherwise stated.

3. Results and discussion

3.1. Absorption and fluorescence spectra

The absorption spectrum of 1 does not change in the pH range 0.1 - 8.8, but it changes in the pH range from 0.1 to $H_0 - 1.72$ (where H_0 is the Hammett acidity function) with an isosbestic point at 28 410 cm^{-1} . Below $H_0 - 1.72$ the spectrum exhibits an increasing blue shift. The $\text{p}K_a$ of 1 in the ground state was determined to be -2.2 .

The fluorescence spectrum does not change in the pH range 1.6 - 8.8, but it exhibits a progressive red shift at $\text{pH} < 1.6$; 1 may be protonated in the excited singlet state at $\text{pH} < 1.6$.

3.2. Photolysis under continuous irradiation

The spectra observed on irradiating an aerated aqueous solution of 1 in the pH range 0.1 - 8.8 at 365 nm are shown in Fig. 2. The spectra observed in a deaerated aqueous solution are the same as those in the aerated solution.

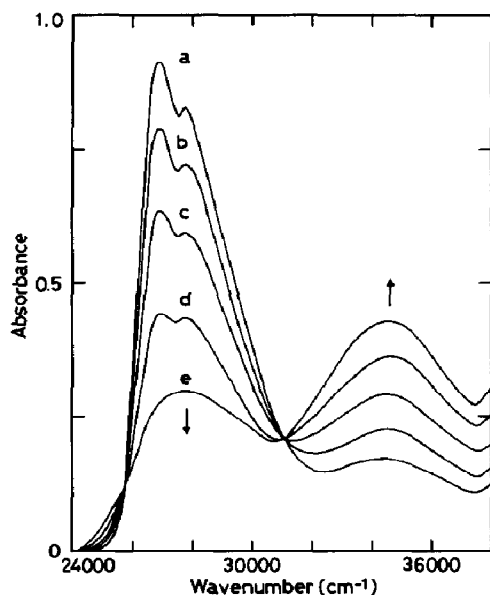


Fig. 2. Spectra of an aqueous solution of 1 on irradiation at 365 nm for various times: curve a, 0 min; curve b, 1 min; curve c, 2 min; curve d, 5 min; curve e, 10 min.

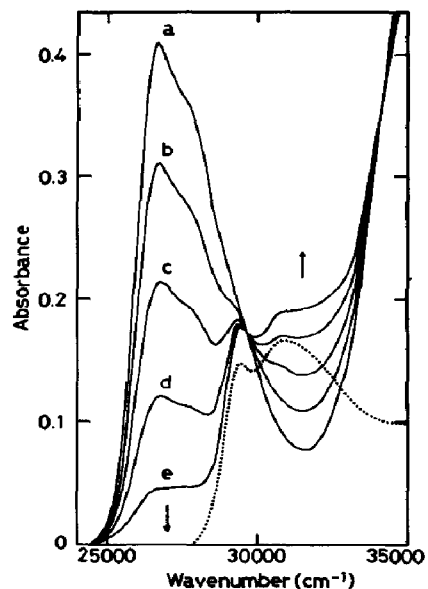


Fig. 3. Spectra of a solution of 1 in 7:13 ethanol:water containing 10^{-4} M TP on irradiation at 365 nm for various times (initial concentration of quinoxaline-1,4-dioxide, 3×10^{-5} M): curve a, 0 min; curve b, 0.7 min; curve c, 1.5 min; curve d, 3 min; curve e, 6 min; ·····, absorption spectrum of quinoxaline-*N*-oxide.

Isosbestic points appeared at 43100, 39220, 31150 and 25710 cm^{-1} . A similar spectral change was observed in 7:13 ethanol:water. The photoproduct was assigned as 3 [8].

The quantum yields Φ for the disappearance of 1 in water and in 7:13 ethanol:water were the same within experimental error and were determined to be 0.22. Since the reaction is not affected by the presence of oxygen, it is clear that oxygen does not participate in the reaction. This is consistent with the conclusion that photoinduced rearrangements of aromatic amine *N*-oxides occur in the excited singlet state [1]. The value of Φ for the aqueous solution does not change in the pH range from 8.8 to $H_0 - 0.5$ but decreases below $H_0 - 0.5$. No reaction occurred below $H_0 - 3.0$. This is similar to the observation of Ono and Hata [9] for isoquinoline-*N*-oxide. It is concluded that protonated quinoxaline-1,4-dioxide does not react in the excited singlet state.

It is well known that TP removes oxygen from oxaziridine- or epoxide-type compounds. Hence photolysis of the solution containing TP was expected to yield quinoxaline-*N*-oxide (4) in addition to 3 if the photoreaction of 1 proceeds through 2. As TP does not dissolve in water, the effect of the TP concentration on Φ was studied in 7:13 ethanol:water. Figure 3 shows the spectra obtained in the solution containing 10^{-4} M TP at 40 °C. The spectrum of the photoproduct is the superposition of those of 3 and 4 [10] as expected. Table 1 lists the values for Φ at various concentrations of

TABLE 1

The quantum yields for the disappearance of quinoxaline-1,4-dioxide at various concentrations of triphenylphosphine

[TP] (μM)	Φ
0	0.22 ₀
1.3	0.24 ₁
3.3	0.26 ₄
6.0	0.28 ₈
13.3	0.30 ₉
26.6	0.31 ₆
66.5	0.34 ₆

TP. Φ approaches a constant value Φ_{∞} with increasing TP concentration. It was found that $\Phi/(\Phi_{\infty} - \Phi)$ is a linear function of the TP concentration as shown in Fig. 4:

$$\frac{\Phi}{\Phi_{\infty} - \Phi} = a + b[\text{TP}] \quad (1)$$

where $\Phi_{\infty} = 0.36$, $a = 1.6$ and $b = 3.5 \times 10^5 \text{ M}^{-1}$.

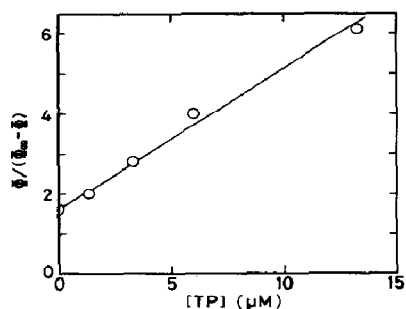


Fig. 4. Plot of $\Phi/(\Phi_{\infty} - \Phi)$ vs. [TP].

3.3. Flash photolysis

Flashing of the deaerated neutral aqueous solution gave the transient absorption spectrum shown in Fig. 5, curve a. The decay is first order with a rate constant of $1.3 \times 10^4 \text{ s}^{-1}$. This transient spectrum was assigned as the triplet-triplet (T-T) absorption spectrum of 1 in view of the results of triplet energy transfer experiments using 1,5-naphthalene disulphonate as an energy donor or methylene blue as an energy acceptor.

Flashing of the aerated aqueous solution gave no transient absorption spectrum below $23\,800 \text{ cm}^{-1}$. In the range $25\,700 - 29\,400 \text{ cm}^{-1}$, where there is an intense absorption by 1, transient fading was observed as shown in Fig. 6(a). The recovery rate of the absorption is first order with a rate constant of $1.1 \times 10^3 \text{ s}^{-1}$. In the range $23\,800 - 25\,700 \text{ cm}^{-1}$ a growth in the

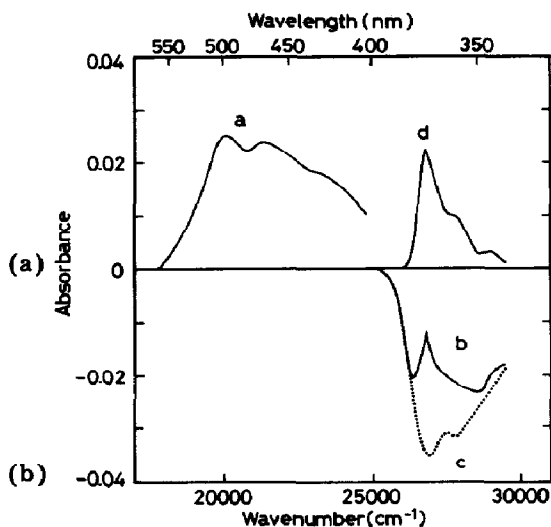


Fig. 5. Transient spectra of an aqueous solution of 1: curve a, T-T absorption spectrum; curve b, transient difference spectrum; curve c, inverted ground state absorption spectrum; curve d, obtained by subtracting curve c from curve b.

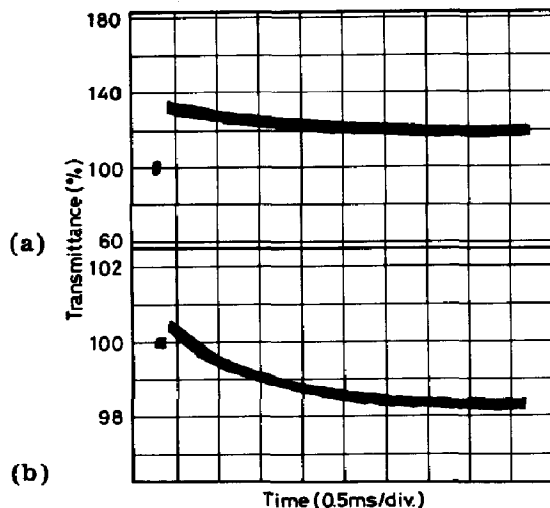


Fig. 6. Typical oscillograms for 1 in aerated water measured at (a) 26 600 cm^{-1} and (b) 24 900 cm^{-1} .

absorption was observed after flashing as shown in Fig. 6(b). The growth rate is first order with a rate constant of $1.1 \times 10^3 \text{ s}^{-1}$. Since the molar extinction coefficient of the photoproduct 3 is larger than that of the reactant 1 in the range 23 800 - 25 700 cm^{-1} , the increase in the absorption is due to the formation of 3.

Figure 5, curve b, shows the transient difference spectrum observed immediately after flashing of 1 and Fig. 5, curve c, shows the inverted absorption spectrum of 1. It should be noted that the shape of the transient difference spectrum is the same as that of the inverted absorption spectrum below 26 000 cm^{-1} but is different above 26 000 cm^{-1} ; there is a transient absorption above but not below 26 000 cm^{-1} . The difference spectrum of curves b and c gives the transient absorption spectrum shown as curve d in Fig. 5. Since the decay rate of this transient is the same as the formation rate of 3, it is obvious that the transient 2 is the precursor of 3.

Whether or not 1 is reproduced from 2 is examined as follows. The absorbance of 1 at 25 640 cm^{-1} before flashing is

$$A_0(25\,640) = \epsilon_1(25\,640)[1]_0 d$$

where $\epsilon_1(25\,640) = 1330 \text{ M}^{-1} \text{ cm}^{-1}$ and $d = 10 \text{ cm}$. Immediately after flashing, 2 is produced but not 3. Therefore the absorbance immediately after flashing at 25 640 cm^{-1} , where 2 does not absorb, is

$$A_t(25\,640) = \epsilon_1(25\,640)([1]_0 - [2]_t) d$$

Thus the decrease in the absorbance at 25 640 cm^{-1} immediately after flashing is

$$-\Delta A(25\ 640) = A_0(25\ 640) - A_t(25\ 640) = \epsilon_1(25\ 640)[2]_t d$$

In contrast the increase in the absorbance at $24\ 390\ \text{cm}^{-1}$ a long time after flashing is due entirely to the formation of 3 because 1 and 2 do not absorb at $24\ 390\ \text{cm}^{-1}$ and

$$\Delta A(24\ 390) = \epsilon_3(24\ 390)[3]_{\infty} d$$

with $\epsilon_3(24\ 390) = 144\ \text{M}^{-1}\ \text{cm}^{-1}$. The results of the flash photolysis of the aerated neutral aqueous solution ($[1]_0 = 3.39 \times 10^{-5}\ \text{M}$) give $-\Delta A(25\ 640) = 0.124$ and $\Delta A(24\ 390) = 0.008$. Therefore $[2]_t = 9.32 \times 10^{-6}\ \text{M}$ and $[3]_{\infty} = 5.55 \times 10^{-6}\ \text{M}$. If 2 is completely transformed to 3, $[3]_{\infty}$ must be equal to $[2]_t$. Since $[2]_t$ is greater than $[3]_{\infty}$, it is concluded that 1 is produced from 2. The relative efficiency of formation of 3 and 1 from 2 is 3:2.

Flashing of the aerated 7:13 ethanol:water solution gives a transient absorption spectrum similar to the spectrum shown in Fig. 5, curve d; 2 is also produced in this solution. The decay rate of 2 is first order with a rate constant k_d of $1.0 \times 10^2\ \text{s}^{-1}$ and is increased on addition of TP. The observed decay rate is a linear function of the TP concentration:

$$k_{\text{obs}} = k_d + k_q[\text{TP}] \quad (2)$$

The rate constant k_q was found to be $1.1 \times 10^7\ \text{M}^{-1}\ \text{s}^{-1}$. The decay of 2 is accompanied by an increase in the absorption of 3 and 4 when TP is present.

3.4. Reaction scheme

The results of the continuous irradiation and flash photolysis are satisfactorily interpreted by the reaction scheme shown in Fig. 7.

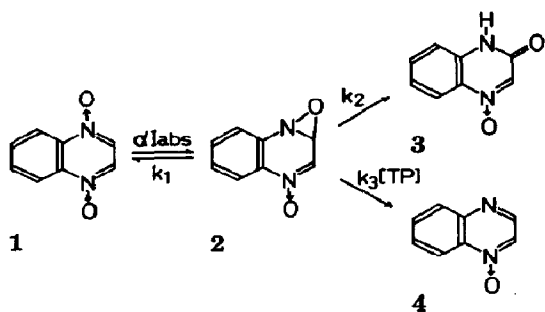


Fig. 7.

α is the quantum yield for the formation of 2, $k_1 + k_2 = k_d$ and $k_3 = k_q$. According to Fig. 7, Φ can be expressed as follows:

$$\Phi = \alpha \frac{k_2 + k_3[\text{TP}]}{k_1 + k_2 + k_3[\text{TP}]} \quad (3)$$

When $k_1 + k_2$ is much less than $k_3[\text{TP}]$, eqn. (3) is reduced to

$$\Phi_{\infty} \approx \alpha \quad (4)$$

From eqns. (3) and (4) we obtain

$$\frac{\Phi}{\Phi_{\infty} - \Phi} = \frac{k_2}{k_1} + \frac{k_3}{k_1} [\text{TP}] \quad (5)$$

Equation (5) agrees with the empirical equation (1), so that we obtain $\alpha = 0.36$, $k_2/k_1 = 1.6$ and $k_3/k_1 = 3.5 \times 10^5 \text{ M}^{-1}$ for the 7:13 ethanol:water solution. We found $k_1 + k_2 = 1.0 \times 10^2 \text{ s}^{-1}$ and $k_3 = 1.1 \times 10^7 \text{ M}^{-1} \text{ s}^{-1}$ for this solution. From $k_2/k_1 = 1.6$ we obtain $k_1 = 38 \text{ s}^{-1}$ and $k_2 = 62 \text{ s}^{-1}$. From $k_3/k_1 = 3.5 \times 10^5 \text{ M}^{-1}$ we obtain $k_1 = 31 \text{ s}^{-1}$. The ratio $k_2/k_1 = 1.6 - 2.0$ is very close to that obtained for the aqueous solution. Therefore the results obtained for continuous irradiation and flash photolysis are consistent. Since it was confirmed that 2 yields both 1 and 3 and reacts with TP to yield 4, 2 is assigned as oxaziridine.

3.5. Transients in the acidic solution

The decay rate of 2 in the acidic solution increases with increasing acid concentration in the pH range from 2 to $H_0 - 0.5$. Figure 8, curve a, shows the transient absorption spectrum obtained immediately after the disappearance of 2. The rate of the growth of this transient absorption is the same as the decay rate of 2 at various acid concentrations. Therefore it is clear that the transient, designated 5, is formed from 2. The slope of the plot of the decay rate *versus* the hydrogen ion concentration gives a value of $1.0 \times 10^4 \text{ M}^{-1} \text{ s}^{-1}$ for the bimolecular rate constant of 2 with the hydrogen ion. The decay of 5 is first order and its rate constant decreases with increasing acid concentration. Since the decay of 5 is accompanied by an increase in the absorption at $24\,390 \text{ cm}^{-1}$, it is concluded that 5 is the precursor of 3. After the disappearance of 5, another transient absorption with a spectrum (Fig. 8, curve b) very similar to that of 5 remained. The decay of this transient, designated 6, is first order with a rate constant of $6.9 \times 10^{-2} \text{ s}^{-1}$ which is barely affected by the acid concentration. As the spectrum of 6 lies in the same spectral range as that of 5, it is not certain whether 6 is formed from 2 or from 5. The decay of 6 is accompanied by an increase in the absorption at

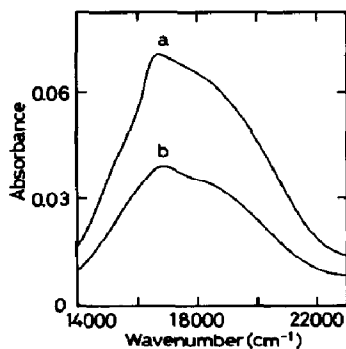


Fig. 8. Transient absorption spectra of 1 in acidic water: curve a, transient 5; curve b, transient 6.

27 030 cm^{-1} while the absorbance at 24 390 cm^{-1} does not change. Therefore it is probable that 6 yields 1 rather than 3.

Kaneko [11] has suggested that the oxaziridine intermediate undergoes a heterolytic cleavage in protic solvents to yield the carbonium ion from which the lactam is formed. His suggestion is supported by our results if 5 is assigned as the protonated form of 2 (Fig. 9). This ion may produce 3. Φ is almost constant in the pH range from 8.8 to $H_0 - 0.5$. Since 1 is partially protonated at $\text{pH} < 1.6$, this fact suggests that the efficiency of the rearrangement from 2 to 3 is increased by the presence of the hydrogen ion.

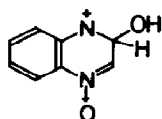


Fig. 9.

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