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The Photochemistry of 2-Quinolinecarbonitriles. II. A Mechanism of the Photoinduced Substitution Reaction

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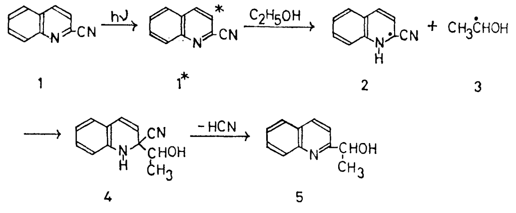
In order to elucidate the mechanism of the photoinduced substitution reaction of 2-quinolinecarbonitrile in alcohols or ethers, measurements of the absorption and fluorescence spectra and the photochemical reactions were carried out in ethanol, *t*-butyl alcohol, or diethyl ether; consequently, an interesting relationship has been found to exist between the fluorescence intensity and the photoreactivity. The photosubstitution reaction can reasonably be assumed to be initiated by a hydrogen-atom abstraction from an alcohol or ether by the nitrogen atom of the quinoline nucleus. The experimental results indicated that such a hydrogen-atom abstraction was markedly facilitated by a hydrogen-bond formation of the nitrogen lone pair of the quinoline nucleus with ethanol or water: further, the reactive excited singlet state (S_1) was presumed to be of a π,π^* nature.

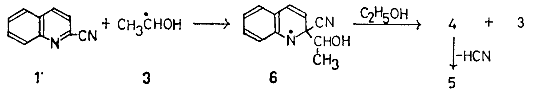
As has been reported in previous papers,[1,2] the irradiation of 2-quinolinecarbonitrile with ultraviolet light longer than 300 nm in alcohol (ethanol, 1-propanol, 2-propanol, or *t*-butyl alcohol) under an oxygen or nitrogen atmosphere resulted in the replacement of the cyano group at the 2-position of a quinoline nucleus by the hydroxyalkyl group. Under a nitrogen atmosphere, however, a certain triazapentaphene was also produced in addition to the photosubstitution product, except for the case of the *t*-butyl alcohol solution. Further, the photosubstitution reaction has been revealed, by triplet-quenching studies, to proceed directly from the lowest excited singlet state (S_1) of 2-quinolinecarbonitrile, whereas the lowest triplet state (T_1) was responsible for the formation of a triazapentaphene. The purpose of the present investigation is to elucidate the mechanism of such a photochemical substitution reaction.

Results and Discussion

It has recently been shown that the ultraviolet irradiation of quinoline itself in ethanol or *t*-butyl alcohol resulted in the corresponding hydroxyalkyl substituted products,[3] and also that 3,5-dicarbomethoxypyridines in alcohol were susceptible to the photochemical addition of alcohol.[4] These photoinduced reactions have been anticipated to be initiated by a hydrogen-atom abstraction from the solvent by the nitrogen atom of heterocycles. Such an assumption has been primarily supported by a flash-spectroscopic detection of the acridanyl radical formed during the photoreduction of acridine in hydrocarbon solvents,[5] and also by the observation of a corresponding radical from pyridine, quinoline, and isoquinoline during their photoreduction in alcohol or ether.[6] In view of these facts, it seems reasonable to assume that the photosubstitution reaction of 2-quinolinecarbonitrile is likewise initiated by a hydrogen abstraction from an alcohol or ether by the nitrogen atom of the quinoline nucleus; for example, as is shown in Scheme 1, an excited 2-quinolinecarbonitrile **1*** in ethanol abstracts a hydrogen atom from ethanol to give a quinolinium radical **2** which is then coupled with the 1-hydroxyethyl radical **3**, after which it loses a hydrogen cyanide to afford a 2-(1-hydroxyethyl)quinoline **5**.[7] In addition, an alternate pathway (Scheme 2), in which the 1-hydroxyethyl radical **3** thus formed attacks an unexcited 2-quinolinecarbonitrile **1**, can also be supposed to account for the substitution reaction.



Scheme 1



Scheme 2

In order to clarify whether or not the mechanism of Scheme 2 is operative in the photosubstitution reaction, the following experiments were undertaken. To a solution of 2-quinolinecarbonitrile (70 mg) in anhydrous ethanol (20 ml), we added 20 mg of di-*t*-butyl peroxyoxalate (DTBP); the mixture was kept at 35 °C for 4 hr under bubbling in oxygen or nitrogen, because DTBP is well known to decompose thermally to produce a *t*-butoxyl radical, which then abstracts a hydrogen atom from an ethanol to give a 1-hydroxyethyl radical.[8] Consequently, not even trace amounts of the substituted product, 2-(1-hydroxyethyl)-quinoline, were detected by means of gas chromatography (column: Silicone SE-30 on Chromosorb P). This appears to indicate that the mechanism of Scheme 2 is not responsible for the photosubstitution reaction.

Next, in order to obtain information about the nature of the reactive excited singlet state (S_1) of 2-quinolinecarbonitrile, measurements of the absorption and and fluorescence spectra and the photochemical reactions were carried out under various conditions at room temperature. The ultraviolet absorption spectrum of 2-quinolinecarbonitrile in anhydrous ethanol is shown in Fig. 1. Both the spectral shape and the maximum wavelength were essentially unchanged in either anhydrous diethyl ether or anhydrous *t*-butyl

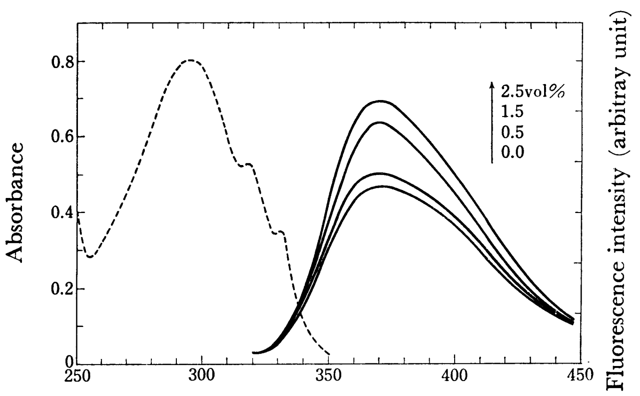


Fig. 1. The absorption and the fluorescence spectra of 2-quinolinecarbonitrile in ethanol at room temperature (concentration of 2-quinolinecarbonitrile: 1.9× 10^{-4} M).

----: The absorption spectrum.

——: The fluorescence spectrum. Numbers refer to the concentration of water (vol%).

alcohol, although a slight change in the molar extinction coefficient was observed. On the other hand, the fluorescence spectrum of 2-quinolinecarbonitrile showed a markable dependence on the solvent used. A fairly strong fluorescence specturm was observed around 370 nm in anhydrous ethanol (Fig. 1), but the intensity was greatly diminished in anhydrous *t*-butyl alcohol and much more so in anhydrous diethyl ether. Moreover, the introduction of small amounts of water into these solutions caused the fluorescence intensity to increase, just as in the case of quinoline itself.⁹⁾ As an example, Fig. 1 shows the fluorescence enhancement with an increase in the concentration of water in ethanol, but the absorption spectrum of 2-quinolinecarbonitrile remained entirely unchanged under these circumstances. Curve (a) in Fig. 2 shows the results when the degree of increase in the fluorescence intensity is plotted against the concentration of water. Quite similar results were also obtained in the case of the *t*-butyl alcohol solution (Curve (a) in Fig. 3). The results described above indicate clearly that the 2-quinolinecarbonitrile becomes fluorescent in hydroxylic solvents, except in *t*-butyl alcohol, which can form a hydrogen bond with the nitrogen lone pair of the quinoline nucleus. The very weak fluorescence in anhydrous *t*-butyl alcohol, however, is probably to be ascribed to the shielding of the hydroxyl group responsible for the hydrogen-bond formation by the bulky *t*-butyl group.

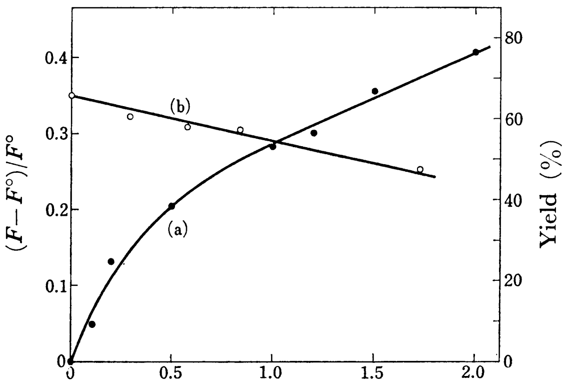


Fig. 2. The effect of small amounts of water on both the yield of photoproduct and the fluorescence intensity in ethanol at room temperature. F and F° represent the relative fluorescence intensity in the presence and the absence of water.

(a) —●—: The degree of increase in the fluorescence intensity.

(b) —○—: The yield of photoproduct.

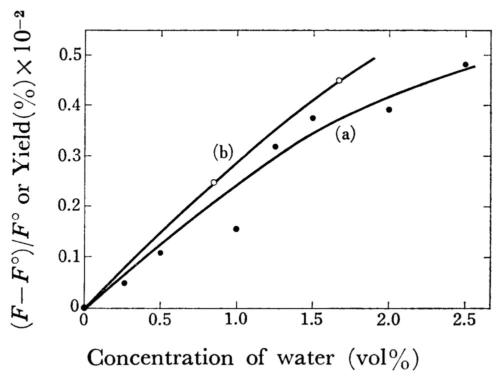


Fig. 3. The effect of small amounts of water on both the yield of photoproduct and the fluorescence intensity in *t*-butyl alcohol at room temperature. F and F° represent the relative fluorescence intensity in the presence and the absence of water.

(a) —●—: The degree of increase in the fluorescence intensity.

(b) —○—: The yield of photoproduct.

The fluorescence activation of quinoline by hydroxylic solvents has been accounted for by assuming that the lowest excited singlet state $S_1(n, \pi^*)$ is raised considerably by the hydrogen-bonding interaction, so that the relative positions of the singlet n,π^* and π,π^* states are reversed and decrease the spin-orbit coupling and, hence, the rate of the intersystem crossing to the triplet manifold.⁹⁾ Recent studies by means of photoelectron spectroscopy,¹⁰⁾ however, appear to suggest that the lowest excited singlet state (S_1) of quinoline is of a π,π^* rather than n,π^* nature. Therefore, the fluorescence activation of quinoline by hydroxylic solvents may be interpreted as follows. The $S_1(\pi,\pi^*)$ state is probably close to the upper singlet n,π^* state, so that some mixing between them may occur through the vibronic coupling. Lim and Yu have described that such a vibronic coupling between the singlet π,π^* and n,π^* states can possibly occur in nitrogen heterocycles.¹¹⁾ This mixing could become smaller in hydroxylic solvents, because the energy difference between the π,π^* and n,π^* states beomes larger because of a hydrogen bonding interaction, and could decrease the n,π^* character in the $S_1(\pi,\pi^*)$ state, resulting in a decrease in the rate of the intersystem crossing to the triplet manifold. Quite similar considerations can possibly account for the fluorescence activation of 2-quinolinecarbonitrile by hydroxylic solvents; that is, the S_1 state of 2-quinolinecarbonitrile is also assumed to be of a π,π^* configuration mixed with the n,π^* singlet state through the vibronic coupling; such an n,π^* nature in the $S_1(\pi,\pi^*)$ state may decrease in hydroxylic solvents, which can form a hydrogen bond with the nitrogen atom of the quinoline nucleus, resulting in the fluorescence enhancement.

As has been reported in a previous paper,[2] the 2-quinolinecarbonitrile in commercial diethyl ether (containing *ca.* 0.2 vol% of water) undergoes photochemical substitution to afford the 2-(2-ethoxyethyl)quinoline in a 32% yield. When anhydrous diethyl ether was used as the reaction medium, however, the yield was greatly reduced to *ca.* 3.6%. In the case of the anhydrous *t*-butyl alcohol solution, also, the yield of the photoproduct, 2-(2-hydroxy-2-methylpropyl)quinoline, was found to be vanishingly low (*ca.* 0.8%), but it increased markedly as small amounts of water were introduced into the solution (Curve (b) in Fig. 3). These results imply that the presence of minute amounts of water in the solution (therefore leading to the hydrogen-bond formation with the nitrogen atom of quinoline nucleus) serves to facilitate remarkably the photosubstitution reaction of 2-quinolinecarbonitrile. In addition, it should be noticed that such an effect of water on the photoreactivity is closely parallel to that on the fluorescence intensity, indicating that the hydrogen-atom abstraction leading to the substitution reaction takes place in the fluorescent state $S_1(\pi,\pi^*)$.

On the other hand, the photosubstitution reaction in anhydrous ethanol occurred in a good yield (*ca.* 66%);[2] however, interestingly, the yield was found to decrease with the addition of small amounts of water to the solution (Curve (b) in Fig. 2). The results could be well explained as follows. In anhydrous ethanol, an excited 2-quinolinecarbonitrile can form a hydrogen bond with an ethanol; such a hydrogen-bonded ethanol molecule may be inferred to be subject to α-hydrogen abstraction by the nitrogen atom, thus resulting in the photosubstitution product in a good yield. When small amounts of water are present in the solution, the hydrogen bonding interaction also exists between excited 2-quinolinecarbonitrile and water. Such an excited 2-quinolinecarbonitrile hydrogen-bonded with water instead of ethanol is also assumed to be responsible for the hydrogen-atom abstraction from a solvent, just as in the case of diethyl ether or *t*-butyl alcohol solution. Therefore, it may be expected that, with an increase in the concentration of water, the yield approaches the value in a *t*-butyl alcohol or diethyl ether solution. In fact, the yield in an ethanol solution containing *ca.* 1.7 vol% of water was about 47%, a value approximately comparable in *t*-butyl alcohol containing *ca.* 1.7 vol% of water (*ca.* 45%) or in commercial diethyl ether (*ca.* 32%). This seems to support the above assumption. Quite similar considerations can be also made in the case of an 1-propanol solution, where the photosubstitution product arising from the β-hydrogen abstraction, different from that in an ethanol solution, may be expected in addition to that from the α-hydrogen abstraction. However, it has been shown in a previous paper[2] that only the 2-(1-hydroxy-2-methylethyl)quinoline arising from the α-hydrogen abstraction was obtained in a yield of 45%. This is probably because the β-hydrogen abstraction is quite difficult because of the steric hindrance of a cyano group at the 2-position of the quinoline nucleus. As will be described in a later paper,[13] the photochemical reaction of 4-quinolinecarbonitrile in 1-propanol provides a 2-(1-hydroxy-2-methylethyl)quinoline-4-carbonitrile and a 2-(1-hydroxymethylethyl)quinoline-4-carbonitrile in yields of 24% and 16%, indicating that the β-hydrogen abstraction takes place as well as the α-hydrogen abstraction. This also supports the idea that the photosubstitution reaction of quinolinecarbonitriles in such anhydrous alcohols as ethanol and 1-propanol is initiated by a hydrogen-atom were abstraction from the alcohol hydrogen-bonded with the nitrogen atom of the quinoline nucleus.

Experimental

The 2-quinolinecarbonitrile used in this experiment was prepared and purified according to the method given in the literature.[14] The ethanol, *t*-butyl alcohol, and diethyl ether used as solvents were reagent-grade products of Wako Pure Chemical Industries; the first two were refluxed over magnesium for dehydration, while the last was dehydrated by sodium and then calcium hydride. The di-*t*-butyl peroxyoxalate used in the thermal reaction of 2-quinolinecarbonitrile in anhydrous ethanol was kindly supplied by Dr. Katsumi Tokumaru of the University of Tokyo.

The ultraviolet absorption and fluorescence spectra were, respectively, measured with a Hitachi recording spectrophotometer EPS-3T and a Hitachi fluorescence spectrophotometer MPF-2A.

The photolytic procedure was similar to that described in a previous paper;[2] 2-quinolinecarbonitrile (0.5 g) dissolved in 350 ml of ethanol, *t*-butyl alcohol, or diethyl ether containing various amounts of water in a Pyrex vessel was irradiated with a 100W high-pressure immersion mercury lamp (Riko Kagaku Sangyo Co.) for 2 hr while oxygen was being bubbled in; the photoproduct and the starting material were then separated by means of silica gel chromatography.

In conclusion, the authors wish to thank Dr. Katsumi Tokumaru and Mr. Hiroyuki Ohta of the University of Tokyo and Professor Akira Sugimori of Sophia University for their kind discussions.

References

1) N. Hata, I. Ono, and S. Ogawa, This Bulletin, **44**, 2286 (1971).

2) N. Hata, I. Ono, S. Matono, and H. Hirose, *ibid.*, **46**, 942 (1973).

3) F. R. Stermitz, C. C. Wei, and C. M. O'Donnell, *J. Amer. Chem. Soc.*, **92**, 2745 (1970).

4) T. J. van Bergen and R. M. Kellogg, *ibid.*, **92**, 8451 (1972).

5) A. Kira, S. Kato, and M. Koizumi, This Bulletin, **39**, 1221 (1966); A. Kira and M. Koizumi, *ibid.*, **40**, 2486 (1967); M. Koizumi, Y. Ikeda, and H. Yamashita, *ibid.*, **41**, 1056 (1968).

6) G. Allan, A. Castellano, J. P. Catteau, and A. Lablache-Combier, *Tetrahedron*, **27**, 4687 (1971); S. Caplain, A. Castellano, J. P. Catteau, and A. Lablache-Combier, *ibid.*, **27**, 3541 (1971).

7) Natsume and Wada have reported that the 3-quinolinecarbonitrile in methanol underwent the photochemical addition of methanol to afford a 1,2-dihydro-2-hydroxymethylquinoline-3-carbonitrile, but a 2-hydroxymethylquinoline-3-

carbonitrile was not produced. M. Natsume and M. Wada, *Tetrahedron Lett.*, **1971**, 4503.

8) W. A. Pryor, "Free Radicals," McGraw-Hills (1966), p. 165.

9) N. Mataga and S. Tsuno, This Bulletin, **30**, 368 (1957).

10) F. Brogli, E. Heilbronner, and T. Kobayashi, *Helv. Chim. Acta*, **55**, 274 (1972).

11) E. C. Lim and J. M. H. Yu, *J. Chem. Phys.*, **45**, 4742 (1966); **47**, 3270 (1967).

12) The yield decreased with an increase of the irradiation time: for example, 66% at 2 hr, 51.6% at 4 hr and 45.4% at 8 hr. This is probably because that the photoproduct undergoes a secondary reaction with oxygen to form the diol, just as in the case of 2-hydroxymethylquinoline reported by Hamana and Noda. M. Hamana and H. Noda, *Chem. Pharm. Bull.* Tokyo, **17**, 2633 (1969).

13) N. Hata, I. Ono, and H. Suzuki, This Bulletin, in press.

14) H. Menze, *Ber.*, **69**, 1566 (1936).