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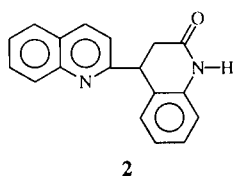
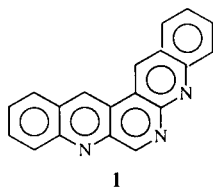
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When 6-phenanthridinecarbonitrile (**3**) is irradiated at 2537 Å in neutral 9:1 2-propanol/water, three major products are formed. These are dimethyl-(6-phenanthridinyl)methanol (**4**), phenanthridine (**5**) and 6,6'-bi-phenanthridine (**6**). When benzophenone is present in the reaction mixture, diphenyl-(6-phenanthridinyl)-methanol is also formed. 6-Phenanthridinyl radical which is common to the formation of all these products, is formed by a monophotonic process involving hydrogen atom abstraction from an alcohol molecule by an excited state of **3**. Unlike what is generally found with other nitrogen-heterocycles, the photochemistry of **3** appears to involve only a π,π^* singlet state. The fluorescence of **3** is quenched with the triplet quencher *cis/trans*-piperylene as a function of the concentration of the diene without the accompaniment of an exciplex emission.

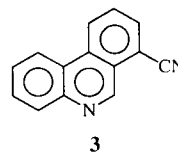
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Introduction.

The literature contains a number of studies describing the photochemistry of 6-membered monoazaaromatic compounds. The effect of substituents, particularly the carbonitrile group, has been the subject of many of these studies [3]. We became interested in these molecules because interesting and often unpredictable results are obtained with many of them. For example, Hata and co-workers reported that when 2-quinolinecarbonitrile is irradiated under neutral conditions in 1° or 2° alcohols, substitution at the 2 position occurs [4-7] as well as dimerization to form the triazapentaphine (**1**) [8], while we found that this same compound yields a dimer lactam (**2**) as the sole product when irradiated in acidified alcohol solution [9]. The corresponding reaction with 2-pyridinecarbonitrile, however, formed substitution as well as coupling products [10].



Since substituted pyridines and quinolines are photoreactive in alcohol solution, but react differently from each other, we thought it would be interesting to study the effect of adding an additional fused ring to the 2-quinolinecarbonitrile molecule to produce a phenanthridine derivative. In this paper we report the results of our work on the photochemistry of 6-phenanthridinecarbonitrile (**3**).

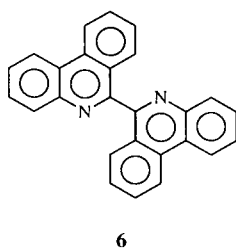
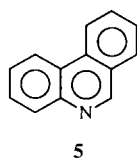
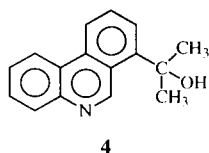


Results and Discussion.

All the reactions were run in 9:1 (v/v) 2-propanol/water unless otherwise stated. All aqueous solutions were deoxygenated by bubbling dry argon gas through the solution for a minimum of 40 minutes. Deaerating by freeze-thaw cycles was not feasible since cells shattered as a result of the freezing process in liquid nitrogen. Reactions were run a minimum of three times to insure reproducible results. All percent yields are based on the amount of starting material used.

When **3** is irradiated at 2537 Å in neutral 2-propanol, three major products are formed. One of these, a substitution product, is dimethyl-(6-phenanthridinyl)methanol (**4**). The other two products formed in this reaction are phenanthridine (**5**), the result of reduction, and 6,6'-bi-phenanthridine (**6**), a product of bimolecular coupling. Other highly colored products were also isolated which

had a combined yield of less than 1% and which were not identified further. The distinct odor of hydrogen cyanide was also noted upon workup of the reaction mixture.



The formation of **4** involves the coupling of two phenanthridinyl radicals formed by the abstraction of a hydrogen atom from the secondary carbon of 2-propanol by **3** in an excited state. It is reasonable to expect that the phenanthridinyl and dimethyl ketyl radicals, formed in this way, would exist as a radical pair in a solvent cage and then couple at the 6 position of the phenanthridinyl radical, where a substantial spin density should reside due to the stabilizing effect of the nitrile group.

The combination of these two radicals within the solvent cage followed by elimination of the cyanide group leads to the formation of **4**. Other products that we observed can be explained by considering reactions of radicals that have left the cage. For example, the dimethyl ketyl radicals could couple, undergo disproportionation, or could electron transfer to **3** in its ground state to generate the corresponding radical ion and acetone. The cyanophenanthridinyl radical could also react by coupling with another similar radical, followed by the elimination of two molecules of hydrogen cyanide to give the dimer **6**.

The photoinduced decyanation of **3** in which the product involves replacement of the nitrile group with a hydrogen atom is not normally observed. Typically, either substitution or dimerization reactions occur. Davidson and co-workers were able to convert 1-naphthalenecarbonitrile to 1-deuteronaphthalene photochemically [11]. This reaction was carried out in the presence of aliphatic amines or sulfides in acetonitrile-deuterium oxide solvent mixture. The authors propose a mechanism that involves an electron transfer from the amine or sulfide, followed by the addition of a deuterium ion and elimination of cyanide radical to yield the corresponding product [11]. We proposed a somewhat different mechanism for the formation of 2-pyridinecarbonitrile formed as one of the products in the photolysis of 2,4-pyridinedicarbonitrile in acetonitrile containing primary or secondary aliphatic amines. In this case photoinduced electron transfer occurs to form the corresponding radical anion. This intermediate then undergoes hydrogen atom abstraction followed by loss of cyanide ion [12-14]. We suggest that **5** is also formed in this manner.

As previously mentioned, there are several products formed in such small yield that they were not identified. At the beginning of the reaction, the solution was colorless, though it quickly turned to a pale orange color that intensified with irradiation. When the solvent was evaporated, an oily residue was obtained. When this residue was subjected to column chromatography, three yellow to orange bands were eluted. Infrared analysis of residues from these samples showed them to be carbonyl compounds. Furthermore, when extremely dilute solutions of **3** were irradiated, uv analysis indicated that the fused ring system was being destroyed. Qualitative analysis of the reaction mixture on a IBM 3345 Ternary Gradient high pressure liquid chromatograph equipped with an actadecyl, C18, column showed that the highly colored photoproducts had retention times very similar, though shorter, than that observed for **5**, and substantially shorter than that of **6**. From this evidence it appears that the phenanthridinyl fused ring system undergoes splitting, probably between the **5** and **6** ring positions, in a type of reverse Schiff base reaction.

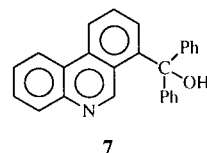
On further consideration of the mechanism of this reaction, it is well established that protonated pyridine bases are much better electron acceptors compared with the corresponding neutral molecules. It has been shown that **5** and other benzoquinolines are all weak bases in their ground states. Marzacco and co-workers have shown that the basicity of these molecules increases when they are promoted to their respective lowest excited singlet states as determined by Förster cycle measurements [15]. This type of behavior would indicate that even though the molecule was not protonated in the ground state, it would likely become protonated upon photoexcitation.

Ohta and co-workers have shown that when **3** is irradiated in the presence of electron-rich olefins such as *trans*-anethole and phenyl vinyl ether in oxygen free ethanol, a $[2\pi + 2\pi]$ cycloaddition occurs between the olefinic double bond and the 5-6 bond of the phenanthridine ring [16-17]. The initial product of this reaction is the corresponding azetidine derivative, which can then undergo ring opening between the original 5-6 bond to yield a tetrahydroazocine derivative involving the addition of ethanol. This reaction is not inhibited by the presence of *cis/trans*-piperylene, clearly indicating a singlet state involvement. Based on their results, the authors have proposed the formation of an exciplex between **3** and the olefin involved. The formation of an exciplex could occur in competition with the diene quenching of the triplet state. The result would allow the formation of photoproducts, though with a much lower quantum efficiency.

In order to obtain additional information about the photoreactive state in this work, the irradiation of **3** was carried out in 9:1 2-propanol/water with a molar excess of *cis/trans*-piperylene which was added to the reaction mixture. At the end of this reaction, the mixture had the usual deep orange color. However, analysis by thin layer chromatography showed that very little reaction had occurred, indicating that the reaction was quenched by the presence of the diene. Significantly, however, we found that the fluorescence of **1** is also quenched under these same conditions without exciplex emission. The mechanism by which *cis/trans*-piperylene quenches the fluorescence of **3** is not clear at this time. It seems, however, that this result could be explained by a mechanism which involves a non-emitting exciplex formed between **3** and the diene. The exciplex must then have a radiationless deactivation path. We also found that the presence of acid quenches fluorescence. This may be due to the protonation of the excited singlet state which would need to take place at a rate faster than that at which fluorescence occurs.

In order to obtain additional information about the excited state that is involved in the photochemistry of **3**, the photoreaction was carried out under the usual conditions described above except that the reaction mixture contained 1.5 molar excess of benzophenone. Analysis by column chromatography showed that the same products had been produced as in those reactions run without benzophenone except that two additional benzophenone related products were formed including diphenyl-(6-phenanthridinyl)methanol (**7**), as well as the benzophenone photoreduction product, benzopinacol. Most of the benzophenone, however, was recovered unchanged. The presence of benzophenone would provide a more efficient method of populating the triplet state. Both benzophenone and **3** absorb light at the irradiating wavelength of 350 nm, but because of its higher quantum efficiency, more of the light

would be absorbed by benzophenone which would then transfer its energy to **3** in its ground state. This would result in the formation of the triplet state of **3** and the ground state of benzophenone. This process could then be reversed yielding the triplet state of benzophenone and the ground state of **3**. Evidence that this process is occurring is found in the fact that if benzophenone did not transfer its energy, it should have undergone quantitative photoreduction in the time allotted for the irradiation. The fact that a small amount of benzopinacol is formed in the photoreaction is not surprising since as the concentration of **3** decreases during the irradiation, triplet benzophenone has fewer molecules of **3** with which to interact.



The benzophenone, *cis/trans*-piperylene and acid experiments described above all support the singlet state as the "normal" photoreactive state. The physical and photo-physical properties of **3** will be presented in paper two of this series.

EXPERIMENTAL

Routine Laboratory Procedures.

Routine proton nmr were recorded on a Varian EM 360-A or a EM 390 NMR spectrometer. The carbon-13 spectra were run on a Varian CFT 20 NMR. All chemical shifts are reported in parts per million (ppm) relative to the shift observed for tetramethylsilane. Deuterated solvents were obtained from Aldrich Chemical Company. Infrared spectra were recorded on a Beckman Acculab IV or a Perkin Elmer Model 381 Infrared spectrophotometer. Polystyrene was used for the calibration of both portions of the spectral recording range. Liquid samples were run neat on either sodium chloride or potassium bromide windows and solids were run as pellets made with spectrograde potassium bromide. Ultraviolet-visible absorption spectra were run on a Cary 15 or 210 Model Recording Spectrophotometer, a Beckman DU series Spectrophotometer or a Perkin-Elmer Lambda-5 UV-Visible Spectrophotometer [18] interfaced to a Dell 12 MHz 80286/80287 to allow acquisition of digitized spectra. Melting points were determined on either a Thomas-Hoover or a Mel-Temp capillary melting point apparatus and are uncorrected. High performance liquid chromatography (HPLC) was carried out on a IBM 3345 Tertiary Gradient HPLC equipped with an analytical column (octadecyl stationary phase, 4.5 x 250 mm) and 254 nm wavelength detector (absorbance)

using 5:1 (v/v) acetonitrile/water as the eluent. All vacuum work was done using a standard floor pump with a maximum vacuum of 10^{-3} torr. Elemental analyses were determined by MHW Laboratories.

All irradiations were made using a Rayonet Photochemical Chamber Reactor Model RPR-100. Either 2537 Å lamps (output of approximately 35 watts) or 3500 Å lamps (approximately 24 watts of *black light* phosphor) were used at the excitation wavelength used in steady-state irradiations. The irradiation chamber typically maintained a temperature of 50-60° C during the prolonged illumination times.

Solvents and Materials.

Acetonitrile (Burdick, HPLC grade distilled in glass for HPLC work, Aldrich Chemical Company, 99+ % Gold Label, spectrophotometric quality for luminescence work), cyclohexane (Fisher Scientific, Certified A.C.S. Spectranalyzed), absolute ethanol (U.S. Industrial Chemical Co.), concentrated hydrochloric acid (J.T. Baker Chemical, Analyzed reagent or Mallinckrodt, Reagent Grade, 34.0-35.5%), methanol (Fisher Scientific Company, 99+ % Gold Label, spectrophotometric quality), phenanthridine (Aldrich Chemical Company), phosphorus pentachloride (Aldrich Chemical Company, 98%), *cis/trans*-piperylene (Aldrich Chemical Company, Technical Grade, 90%; remaining material is cyclopentene), 2-propanol (Fisher Scientific, Certified A.C.S. suitable for electronic use), sodium cyanide (Allied Chemical, reagent grade), and concentrated sulfuric acid (Fisher Scientific, Reagent A.C.S. or Mallinckrodt, reagent grade) were all used without further purification. Benzene (Mallinckrodt, reagent grade) was distilled and stored over sodium turnings. Benzoyl chloride (Mallinckrodt, reagent grade) was distilled just prior to use.

Deionized water for luminescence work was heated at reflux overnight over potassium permanganate (Mallinckrodt, Analytical Reagent) (10 grams per liter) then triply distilled in glass.

Synthesis of 6-Phenanthridinecarbonitrile.

Synthesis of 5-benzoyl-6-dihydrophenanthridine was carried out using a modification, chosen for safety considerations, of the Wittig adaptation [19] of the Reissert reaction [20,21] for phenanthridine. Dry hydrogen cyanide [19], which was prepared by adding 200 mL 25% sulfuric acid (1.03 moles), to 52 grams sodium cyanide (1.06 moles) dissolved in 200 mL water and passed over anhydrous calcium, was bubbled into a benzene solution that contained 33.6 grams of phenanthridine (0.187 moles) at a temperature of 5-10° C. During this time, 15 mL of freshly distilled benzoyl chloride (0.129 mole) was added over a period of fifteen minutes.

The solution was allowed to stand for a total of sixteen hours, during which time a white precipitate formed. The reaction mixture was then taken up in diethyl ether and this solution was washed with water, 5 N sulfuric acid, 7.5% sodium bicarbonate and again with water. Diethyl ether and benzene were removed on a rotary evaporator leaving an orange oil as residue. This residue was induced to crystallize by the addition of denatured ethanol and recrystallized from this solvent yielding a pale yellow solid, mp 140-141° C (lit [19] mp 140-141.5° C). The yield for the formation of the Reissert compound was 50%.

The general method of Kaufmann and Dändliker was used for the conversion of benzoyl-6-cyano-5,6-dihydrophenanthridine to

3 [22]. Into a flask containing 3.0 g of 5-benzoyl-6-cyano-5,6-dihydrophenanthridine (9.67 mmoles) was added 60 g of phosphorous pentachloride (28.8 mmoles). The mixture was then heated, which caused the solid to darken slowly and finally liquify at 190° C. The mixture was then heated at reflux for 4 hours at a temperature of 120-130° C, and then quenched by adding it to 15 g of anhydrous sodium carbonate dissolved in 400 mL of ice cold water. The solution was then extracted three times with chloroform and the combined extracts reduced to a yellow oil on the rotary evaporator. This residue was then chromatographed on silica using a series of solvents with increasing polarity including hexane, 50:50 (v/v) hexane/benzene, benzene, 50:50 (v/v) hexane/chloroform, chloroform, 50:50 (v/v) chloroform/diethyl ether, diethyl ether, 50:50 (v/v) diethyl ether/methanol and methanol. The crude **3** eluted from the column in the hexane/benzene and benzene fractions and was recrystallized from ethanol, mp 136.5-137.5° C (lit [23] mp 136-137° C). The yield was 0.237 g (10-12%). Infrared and ¹H nmr spectra were consistent with the reported structure.

Irradiation of 6-Phenanthridinecarbonitrile at 2357 Å.

A solution of **3** (1.03 mmoles) in 150 mL of 9:1 (v/v) 2-propanol-water was deaerated with argon bubbling for a minimum of 30 minutes. The reaction was irradiated for 16 hours at 2357 Å in a Rayonet reactor, during which time the solution changed from colorless to orange. When the reaction flask was opened, the distinct odor of hydrogen cyanide was present. The solvent was removed by evaporation on a rotary evaporator and the residue dissolved in 10 mL of chloroform. The resulting solution was then subjected to chromatographic separation on silica gel using the same conditions used for the purification of **3**. Most of the material that eluted from the column was starting material, based on Infrared comparison with an authentic sample and retention time on the HPLC (9 minutes). Three distinct products were isolated in very small amounts (5-10 mg) in addition to several orange colored products which had a total mass which was inadequate for analysis. Attempts to obtain larger quantities of the initial photoproducts of **3** by longer periods of irradiation were unsuccessful since numerous other products began to form which were shown to be present by the appearance of at least eight major spots on analysis by tlc, with no noticeable build up of the initial products.

The material was then chromatographed on silica gel using the same procedure as was used for the purification of the Reissert compound. The product **5** was identified by comparison with an authentic sample of this compound purchased from the Aldrich Chemical Company. The identification of **6** (hexane/chloroform and chloroform chromatography fractions) was based on nmr and/or Infrared analysis. Product **6** exhibited the same HPLC retention time (22 minutes) as the minor product from the thermal decarboxylation of 6-phenanthridinecarboxylic acid. Insufficient material was obtained for further purification and elemental analysis. None of the products in the HPLC qualitative analysis corresponded to either the amide or carboxylic acid of phenanthridine; 6,6-Biphenanthridine: mp 329-330° C (lit [24] 341° C); ir (KBr) 3020, 1600, 1555, 1475, 1438, 1388, 1345, 1290, 1240, 1190, 1140, 1038, 975, 955, 935, 900, 855, 832 cm^{-1} ; Dimethyl-(6-phenanthridinyl)methanol: ir (KBr) 3500, 1605, 1575, 1515, 1480, 1455, 1440, 1400, 1245, 975, 900, 780, 755, 725 cm^{-1} . ¹H nmr (deuteriochloroform), low solubility, overlapping multiplets at δ 6.6-8.5 (8 H), a broad peak at δ 3.9 (\approx 1.3 H), and a singlet at δ 1.4 (6 H).

Irradiation of 6-Phenanthridinecarbonitrile and Benzophenone at 3500 Å.

A solution of 0.41 g of **3** (2.00 mmoles) and 0.47 g (2.38 mmoles) of benzophenone dissolved in 300 mL of 9:1 (v/v) 2-propanol/water was deaerated with argon bubbling for a minimum of 30 minutes. Then the solution was irradiated for 4 hours at 3500 Å in a Rayonet reactor, during which time the solution changed from colorless to orange. The odor of hydrogen cyanide was evident when the flask was opened. The solvent was removed by evaporation on a rotary evaporator and the residue was taken up in 10 mL of chloroform and chromatographed in the same way as described above for the Reissert compound. It was determined that most of the material isolated was unreacted starting material based on infrared analysis and HPLC retention time (9 minutes). HPLC also exhibited peaks with identical retention times as for the three products isolated in the direct irradiation reaction (phenanthridine at 7 minutes and **3** at 12.5 minutes). In addition, the major product in this reaction was the coupling product formed with diphenyl ketyl radical (0.072 g) (16 minutes HPLC retention time); ms [24] m/z 361 (M^+ , 89), 284 (46), 178 (100), 106 (49), 77 (46); mp 200.5-201.5° C; ir: (KBr) 3360, 3050, 1606, 1572, 1520, 1480, 1440, 1385, 1342, 1310, 1206, 1152, 1050, 1025, 1000, 950, 920, 905, 865, 832, 752, 720, 695 cm^{-1} ; 1H nmr (deuteriochloroform): overlapping multiplets at δ 7.0-8.8 (20 H), 5.7 broad band (1 H).

Anal. Calcd. for $C_{26}H_{19}NO$: C, 86.13; H, 5.47; N, 3.89; O, 4.51. Found: C, 86.40; H, 5.30; N, 3.88.

REFERENCES AND NOTES

- [1] Presented in part at the 17th IUPAC Symposium on Photochemistry, July 19-24, 1998, Barcelona, Spain.
- [2a] Department of Chemistry, University of Rhode Island, Kingston, RI 02881; [b] Department of Chemistry, University of Florida, Tallahassee, FL 32304-7801.
- [3] B. M. Vittimberga, F. Minisci and S. Morrocchi, *J. Am. Chem. Soc.*, **97**, 4397 (1975).
- [4] N. Hata, I. Ono and S. Ogawa, *Bull. Soc. Chim. Japan*, **44**, 2286 (1971).
- [5] N. Hata, I. Ono, S. Matono and H. Hirose, *Bull. Soc. Chim. Japan*, **46**, 942 (1973).
- [6] N. Hata and T. Saito, *Bull. Soc. Chim. Japan*, **47**, 942 (1974).
- [7] N. Hata, I. Ono and H. Suzuki, *Bull. Soc. Chim. Japan*, **47**, 2609 (1974).
- [8] N. Hata and R. Ohtsuka, *Chem. Letters*, 1107 (1975).
- [9] T. Caronna, S. Morrocchi and B. M. Vittimberga, *J. Org. Chem.*, **46**, 34 (1981).
- [10] T. Caronna, S. Morrocchi and B. M. Vittimberga, *J. Heterocyclic Chem.*, **17**, 399 (1980).
- [11] R. A. Beecroft, R. S. Davidson, D. Goodwin and J. E. Pratt, *Tetrahedron*, **40**, 4487 (1984).
- [12] R. Bernardi, T. Caronna, S. Morrocchi, M. Ursini and B. M. Vittimberga, *J. Chem. Soc., Perkin Trans. 1*, 97 (1990).
- [13] T. Caronna, S. Morrocchi and B. M. Vittimberga, *J. Heterocyclic Chem.*, **27**, 1705 (1990).
- [14] R. Bernardi, T. Caronna, S. Morrocchi and B. M. Vittimberga, *J. Chem. Soc., Perkin Trans. 2*, 1411 (1991).
- [15] C. J. Marzacco, G. Deckey and R. Colarulli, *J. Phys. Chem.*, **93**, 2935 (1989).
- [16] K. Okada, K. Okubo and M. Oda, *Tetrahedron Letters*, **30**, 6733 (1989).
- [17] S. Futamura, H. Ohta and Y. Kamiya, *Kokagamu Toronkai Koen Yashishu*, 272 (1979).
- [18] Dr. Jack Saltiel's laboratory at Florida State University.
- [19] G. Wittig, M. A. Jesaitas and M. Glos, *Justus Liebigs Ann. Chem.*, **577**, 1 (1952).
- [20] A. Reissert, *Ber.*, **38**, 1603 (1905).
- [21] A. Reissert, *Ber.*, **38**, 3415 (1905).
- [22] A. Kaufmann and P. Dändliker, *Ber.*, **46**, 2924 (1913).
- [23] E. Hayashi and H. Ohki, *Yakugaku Zasshi*, **81**, 1033 (1961).
- [24] L. G. Vaughan, *J. Organomet. Chem.*, **190**, C56 (1980).