Photoreaction of 2-Nitrophenazine 10-Oxide with Amines

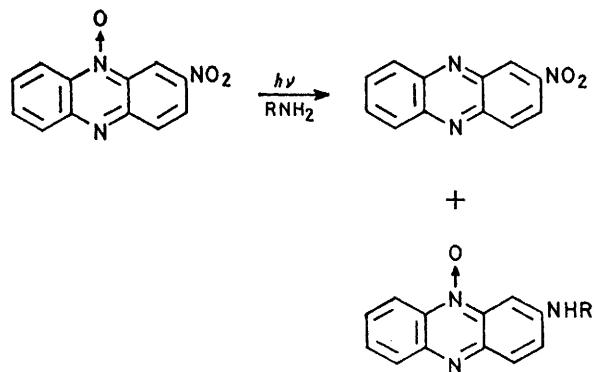By **Silvio Pietra,** **Gian Franco Bettinetti, Angelo Albini, Elisa Fasani,** and **Roberta Oberti,** Istituto di Chimica Organica dell'Università di Pavia, V.le Taramelli 10, 27100 Pavia, Italy

The photodeoxygenation and the photosubstitution of the nitro-group of 2-nitrophenazine 10-oxide has been investigated by kinetics methods supplemented by quenching measurements. Photodeoxygenation by triethylamine occurs quite efficiently (Φ_r ca. 0, 2) in acetonitrile and methanol and is little affected by triethylamine concentration. The other amines employed are much less efficient: their efficiency strongly depends on the amine concentrations. Examination of the fluorescence quenching data with the quantum yields of reduction allows the conclusion that in the case of triethylamine, the main pathway of reduction involves an exciplex derived from the singlet state. The same pathway is also proposed for the reduction by concentrated solutions of other amines in acetonitrile. In different conditions a pathway from a triplet state seems to be more important. Both the pathways lead to the same intermediate. Quenching of the reduction by oxygen and by tetramethyldiazetine dioxide supports this point. The mechanism of photosubstitution of the nitro group is also discussed.

In contrast to the photoisomerization of azine N-oxides, which has received considerable attention,[1,2] little is known about their photoreduction. Minor amounts of the parent azines have been isolated in the photolysis of many N-oxides.[1] In particular conditions, easy photoreduction has been achieved: in fact photolysis of quinoline N-oxides in benzene containing boron trifluoride–ether[3] and of isoalloxazine N-oxides in the presence of cyclohexa-1,4-diene[4] leads to the deoxygenation.

In the course of our research on phenazine N-oxides, we have found that irradiation of 2-nitrophenazine 10-oxide (NPO) in methanol or acetonitrile results only in inefficient deoxygenation to 2-nitrophenazine.[5a] However, in the presence of aliphatic amines, NPO reacts as shown in the Scheme.

The preparative aspects of these reactions have been reported elsewhere;[5b] here a mechanism is proposed on the basis of fluorescence (Φ_f^0 and Φ_f), reduction (Φ_r), and substitution quantum yields (Φ_s) in the presence of variable amounts of n-butylamine, t-butylamine, triethylamine, and piperidine. From Tables 1 and 2 and

with an efficiency in the order: triethylamine $\cong$ piperidine > n-butylamine > t-butylamine. The quenching efficiency is greater in acetonitrile than in methanol.

The fluorescence quenching by the oxygen dissolved in methanol is practically undetectable. In acetonitrile,

TABLE 1

Fluorescence quantum yields of NPO

In MeCN (λ_{max}. 550 nm)		In MeOH (λ_{max}. 570 nm)	
Φ_f	Φ_f [a]	Φ_f	Φ_f [a]
0.25	0.32	0.01	0.01 [b]

[a] Values determined in solution degassed by three freeze-thaw cycles (10^{-3} Torr) in Pyrex Thunberg tubes and by directly measuring the fluorescence in the same tubes: in this way the accuracy is only ca. $\pm3\%$. [b] Within experimental error (see footnote a).
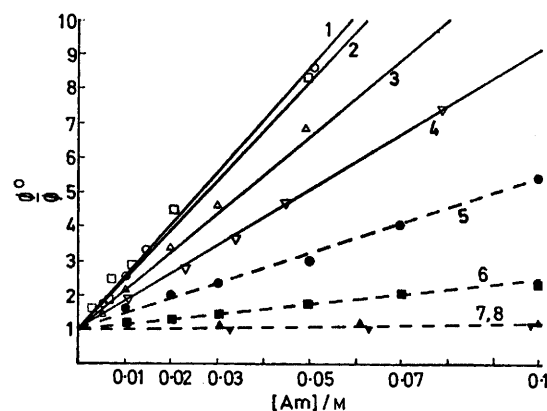

FIGURE 1 Stern–Volmer plots for the quenching of NPO fluorescence by amines: in MeCN (———); 1, triethylamine, slope 170; 2, piperidine, slope 163; 3, n-butylamine, slope 112; 4, t-butylamine, slope 80 1 mol^{-1}; in MeOH (– – – –); 5, triethylamine, slope 44; 6, piperidine, slope 14; 7, n-butylamine, slope ca. 0.5; 8, t butylamine, slope $\leqslant 0.1$ 1 mol^{-1}

SCHEME

Figures 1—4, which summarize the significant data, the following can be observed.

The fluorescence of NPO is quenched by the amines

singlet quenching by oxygen is significant, but it is negligible compared with the quenching by amines.

Φ_r Values for triethylamine are 10—100 times greater than those for the other amines. The order of amine

[1] G. G. Spence, E. C. Taylor, and O. Buchardt, Chem. Rev., 1970, **70**, 231.

[2] F. Bellamy and J. Streith, Heterocycles, 1976, **4**, 1391.

[3] N. Hata, I. Ono, and M. Kawasaki, Chem. Letters, 1975, 25.

[4] M. Gladys and W. R. Knappe, Z. Naturforsch., 1974, **29b**, 549.

[5] (a) A. Albini, A. Barinotti, G. F. Bettinetti, and S. Pietra, J.C.S. Perkin II, 1977, 238; (b) G. Minoli, A. Albini, G. F. Bettinetti, and S. Pietra, ibid., p. 1661.

reactivity is: triethylamine > piperidine > n-butyl-amine > t-butylamine. Φ_r Values for triethylamine are scarcely affected by the concentration of the amine.

occurred directly from the singlet excited state, without formation of a stable intermediate, the $\Phi_{r\ degassed}/$ $\Phi_{r\ undegassed}$ ratio would be *ca.* 1. In fact the quenching

TABLE 2

Quantum yields of reduction (ϕ_r) and substitution (ϕ_s) of 2-nitrophenazine 10-oxide in the presence of amines at different concentrations

Amine	Solvent	0.01M		0.05M		0.1M		0.2M		0.3M		1M [a]	
		D [b]	UD [c]	D [b]	UD [c]	D [b]	UD [c]	D [b]	UD [c]	D [b]	UD [c]	D [b]	UD [c]
						$10^2 \times \Phi_r$							
Triethylamine	CH₃CN	15	2.9	22	6.7	20	7.7	22	7.6	18	6.4	11	2.8
Triethylamine	CH₃OH	23.5	1.5	25.5	1.7	25.5	5.9	25	13	30	15.5	22	16
Piperidine	CH₃CN	0.53	0.14	2.1	0.34	1.5	0.65	2.7	0.69	2.2	0.84		
Piperidine	CH₃OH	0.65	0.20	2.5	0.41	2.2	0.46	3.5	0.62	2.9	0.64		
n-Butylamine	CH₃CN	0.40	0.15	0.73	0.53	1.2	0.61	1.5	0.92	2.1	1.2		
t-Butylamine	CH₃CN	0.21	0.01	0.33	0.03	0.45	0.03	0.51	0.04	0.57	0.08		
						$10^3 \times \Phi_s$							
Piperidine	CH₃CN	0.45	0.10	1.5	0.35	2.2	0.75	4.5	1.0	5.0	1.4		
Piperidine	CH₃OH	0.15	0.10	3.5	1.0	7.1	1.5	15	2.7	13.5	3.2		
n-Butylamine	CH₃CN	0.07	0.02	0.2	0.08	0.37	0.08	0.4	0.12	0.6	0.15		

[a] For the other amines this molarity was not used owing to dark reactions. [b] Degassed runs. [c] Undegassed runs.

The reduction is strongly quenched by the oxygen dissolved in methanol. This is consistent with the formation of long-lived intermediates. If reduction

FIGURE 2 Reciprocal quantum yield of reduction (Φ_r^{-1}) *versus* reciprocal amine concentration [Am]⁻¹: in MeCN (degassed runs); piperidine, slope 0.015, intercept 0.352 (r 0.979); triethylamine, slope 0.002 1 mol⁻¹, intercept 0.045 (r 0.959), for amine concentrations between 0.01 and 0.2M

FIGURE 3 Reciprocal quantum yield of reduction (Φ_r^{-1}) *versus* reciprocal amine concentration [Am]⁻¹ in MeCN (undegassed runs): piperidine, slope 0.06 1 mol⁻¹, intercept 1.181 (r 0.992); n-butylamine, slope 0.059 1 mol⁻¹, intercept 0.798 (r 0.998); triethylamine, slope 0.002 1 mol⁻¹, intercept 0.11 (r 0.997) for amine concentrations between 0.01 and 0.2M

effect on the singlet by the oxygen dissolved in the solvent is small compared with the large singlet quenching by the amines. Plots of Φ_r^{-1} *versus* [amine]⁻¹ are linear in many cases. Least-square analyses are reported in Figures 2—4.

The values of Φ_s for n-butylamine and piperidine are very low and zero for t-butylamine. Values of Φ_s are much affected by the concentration of amine. The substitution reaction is strongly quenched by oxygen.
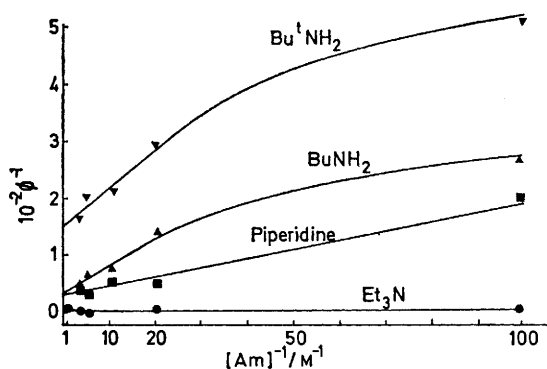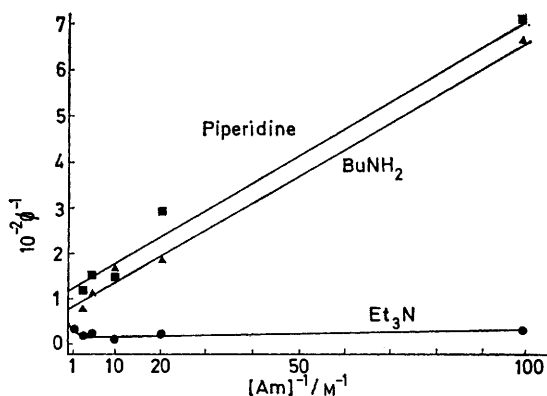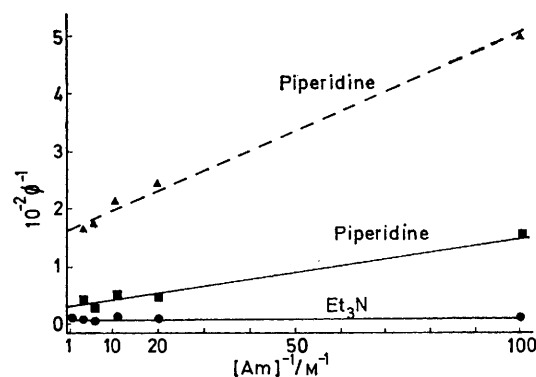

FIGURE 4 Reciprocal quantum yield of reduction (Φ_r^{-1}) *versus* reciprocal amine concentration [Am]⁻¹ in MeOH, (———) degassed runs: piperidine, slope 0.013 1 mol⁻¹, intercept 0.253 (r 0.991); triethylamine, slope 0.004 1 mol⁻¹, intercept 0.039 (r 0.933), for amine concentrations between 0.01 and 0.2M; (— — — —) undegassed runs: piperidine, slope 0.034 1 mol⁻¹, intercept 1.609 (r 0.992)

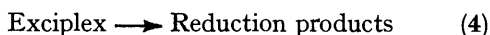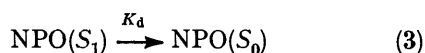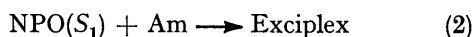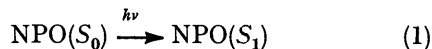This is consistent with the formation of long-lived intermediates.

DISCUSSION

It is well known that amines photoreduce many classes of organic compounds, such as ketones, aldehydes, quinones, nitro-compounds, *etc.* Detailed quantitative studies on photoreduction with amines have been carried out with ketones, whilst the study of other classes of compounds is at an earlier stage.

Cohen [6] proposed that photoreduction of aromatic ketones by amines proceeds through a complex $\left[\begin{array}{c}\text{>C–O}^- \\ \text{>N}^{\!+}\!\text{<H}\end{array}\right]$ formed from the triplet excited state of the ketone.

It is also well known that the aromatic nitro-compounds undergo photoreduction and/or photo-substitution with many reagents. In some cases a complex between the reagent and the triplet excited state of the nitro-compound has been suggested [7,8] as an intermediate in both the reduction and the substitution of the nitro-group.

For the photoreduction of NPO by triethylamine we consider that in acetonitrile the quenching of fluorescence by triethylamine occurs with high efficiency. Therefore the percentage of unquenched S_1 is very low. For instance, 0.1M-triethylamine in acetonitrile quenches 95% of the fluorescence of NPO. At this concentration of triethylamine, Φ_r is 0.21. Thus, at most, 24% of the photoreduction can occur from a triplet state formed by intersystem crossing. (Actually 24% is reduced to 16% if we consider that, in degassed acetonitrile, 32% of the singlet decays by fluorescence.) Most of the reaction with triethylamine then occurs by a different path, the first steps being (1)—(4).

$$\text{NPO}(S_0) \xrightarrow{hv} \text{NPO}(S_1) \tag{1}$$

$$\text{NPO}(S_1) + \text{Am} \longrightarrow \text{Exciplex} \tag{2}$$

$$\text{NPO}(S_1) \xrightarrow{K_d} \text{NPO}(S_0) \tag{3}$$

$$\text{Exciplex} \longrightarrow \text{Reduction products} \tag{4}$$

The percentages of the fluorescent singlet quenched by 0.01—0.3M-amine are reported in Table 3. In

TABLE 3

Percentage of singlet quenched by amines at different concentrations

Amine	Solvent	0.3M	0.2M	0.1M	0.05M	0.01M
Triethylamine	CH_3CN	98	97	95	90	63
Piperidine	CH_3CN	98	97	94	89	62
n-Butylamine	CH_3CN	97	96	92	85	53
t-Butylamine	CH_3CN	96	94	89	80	45
Triethylamine	CH_3OH	93 [a]	90 [a]	81	69	30
Piperidine	CH_3OH	80 [a]	73 [a]	58	41	12

[a] These data were obtained by extrapolating the fluorescence measurements at concentrations <0.2M.

acetonitrile these values are high for amine concentrations $\geqslant$0.05M. Therefore in the following discussion reactions (1)—(4) are also proposed for the other amines, although the low values of Φ_r do not allow us to demonstrate that this is the main pathway, but only to exclude the alternative pathway (5) as the one operating at high
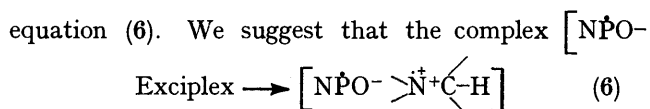
$$(S_1) \xrightarrow{\text{i.s.c.}} (T_1) \xrightarrow{\text{Am}} \text{Reduction products} \tag{5}$$
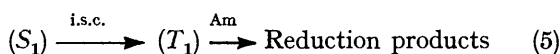
* For a discussion on the decay of exciplexes, see ref. 9.

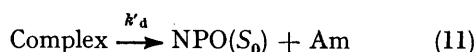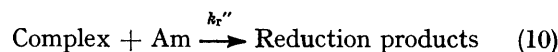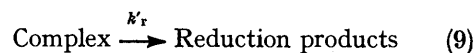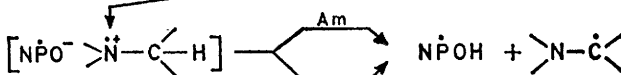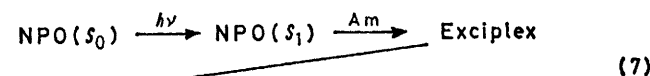[6] S. G. Cohen, A. Parola, and G. H. Parson, jun., *Chem. Rev.*, 1973, **73**, 141.

concentration of piperidine and n-butylamine (in aceto-nitrile).

The next step of the pathway from the exciplex to the reduction products can be reasonably * represented by

equation (6). We suggest that the complex $\Big[\text{N}\dot{\text{P}}\text{O}^-$

$$\text{Exciplex} \longrightarrow \Big[\text{N}\dot{\text{P}}\text{O}^- \ \text{>}\overset{\!+}{\text{N}}\!\text{<}\overset{\diagup}{\text{C}}\text{–H}\Big] \tag{6}$$

$\text{>}\overset{\!+}{\text{N}}\!\text{<}\overset{\diagup}{\text{C}}\text{–H}\Big]$, similar to the complex proposed by Cohen,[6] is the long lived intermediate responsible for both the strong quenching of reduction by oxygen and the amine concentration effect on Φ_r [equation (10)].

At this point, the mechanism for the photoreduction of ketones by amines [6] can be used for the subsequent steps; the main pathway of reduction of NPO by triethylamine (and very likely by other amines) is then (7). Combining equations (2) and (6) in (8) gives the kinetic scheme (1), (3), and (8)—(11). This leads to the rate expression (12).

$$\text{NPO}(S_0) \xrightarrow{hv} \text{NPO}(S_1) \xrightarrow{\text{Am}} \text{Exciplex} \tag{7}$$

$$\text{NPO}(S_1) + \text{Am} \xrightarrow{k_r} \text{Complex} \tag{8}$$

$$\text{Complex} \xrightarrow{k'_r} \text{Reduction products} \tag{9}$$

$$\text{Complex} + \text{Am} \xrightarrow{k_r''} \text{Reduction products} \tag{10}$$

$$\text{Complex} \xrightarrow{k'_d} \text{NPO}(S_0) + \text{Am} \tag{11}$$

$$\frac{1}{\Phi_r} = \frac{k_d + k_r[\text{Am}]}{k_r[\text{Am}]} \cdot \frac{k_r' + k_r''[\text{Am}] + k'_d}{k_r' + k_r'' [\text{Am}]} \tag{12}$$
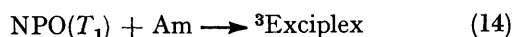
According to equation (12), a linear plot of Φ_r^{-1} *versus* $[\text{Am}]^{-1}$ is expected when k_r'' is small or when the complex population is almost constant. The first condition can be fulfilled only in the case of triethylamine; in this case the linear portion of the curve (Figure 2) has a small slope and the ratio of slope to intercept is *ca.* 0.005 mol l⁻¹, similar to the k_d/k_r value obtained by fluorescence quenching measurements (0.005 9M). The data of Table 3 show that the second condition is not fulfilled by any amine. Therefore, a linear relationship should not be found for n-butylamine, t-butylamine, and piperidine. This is not the case, as the plot of Φ_r^{-1} *versus* $[\text{piperidine}]^{-1}$, in acetonitrile, is linear. Therefore the kinetic expression (12) does not account for all the experimental data. In other words, our data show that

[7] D. Döpp, *Topics Current Chem.*, 1975, **55**, 1.

[8] J. Cornelisse, *Pure Appl. Chem.*, 1975, **41**, 433.

[9] J. B. Birks, 'Photophysics of Aromatic Molecules,' Wiley, London, 1970, p. 435.

the population of the complex is less dependent on the amine concentration than the values of singlet quenching (Table 3) indicate, *i.e.* the complex is partly formed other than in the way described above, *e.g.* by reactions (13)—(15).

$$NPO(S_1) \xrightarrow{\text{i.s.c.}} NPO(T_1) \qquad (13)$$

$$NPO(T_1) + Am \longrightarrow {}^3Exciplex \qquad (14)$$

$${}^3Exciplex \longrightarrow Complex \qquad (15)$$

This raises the question, analogous to that discussed [10] in the photoreduction of ketones by amines, whether the exciplexes derived from the singlet and triplet states of NPO are the same or not, and if they are different whether the singlet exciplex can decay to the triplet exciplex. At our present stage of knowledge of the photoreduction of azine *N*-oxides, this point is unimportant. What is important is to point out that singlet and triplet states can lead to the same * long-lived intermediate for which we suggest the structure $\left[NPO^- \right.$

$\left. \underset{\diagdown}{\overset{+}{N}}{-}\overset{\cdot}{\underset{|}{C}}{-}H \right]$ by analogy with that generally invoked for the

classes of reactions (photoreduction and photoreactions of aromatic nitro-compounds) that occur for NPO. This hypothesis of two different routes to reach the complex, regardless of the existence of one or two exciplexes, can also account for the results obtained in methanol. In this solvent the percentage of singlet unquenched by triethylamine varies from 7 to 70%, whilst Φ_r is always *ca.* 0.25. Also, in methanol the plot of Φ_r^{-1} *versus* [piperidine]$^{-1}$ is linear whilst the percentage

TABLE 4

Quenching of substitution and reduction photoreactions by 0.1M-tetramethyldiazetine dioxide

Amine	Concentration (M)	Solvent	$\Phi_r°/\Phi_r$	$\Phi_s°/\Phi_s$
Triethylamine	0.01	CH$_3$CN	1.1	
	0.01	CH$_3$OH	1.65	
	0.3	CH$_3$OH	1.0	
Piperidine	0.1	CH$_3$CN	1.0	1.3
	0.1	CH$_3$OH	1.25	2.05

of singlet unquenched by piperidine varies from 20 to 88%.

In conclusion, in methanol at low concentration of amine the formation of a complex *via* the triplet state [equation (15)] seems to prevail; in acetonitrile at moderately high concentration of amine, the route indicated by equations (1)—(4) and (7)—(9) is more important. This is supported by quenching of reduction by 3,3,4,4-tetramethyl-1,2-diazetine 1,2-dioxide (TMDD) (Table 4).

* Caldwell [11] discussed, in the case of ketones, the possibility that the ion pairs formed from singlets differ from those formed from triplets and ascribed the difference to a 'spin memory.' This hypothesis is not considered here, as the data on which Caldwell's hypothesis is based, *i.e.* the decrease of Φ_r of fluorenone when high concentrations of amines are employed, are better explained by singlet fluorenone quenching by the amine.[12]

On the whole, quenching by TMDD is poor, but it is significant that the quenching occurs when dilute solutions of amines in methanol are employed.

The very low values of Φ_s do not allow any well grounded mechanism to be advanced for the substitution of the nitro-group. There is, though, a long lived intermediate which reacts with a molecule of amine. We tentatively suggest that this intermediate is the same as that already invoked for reduction.

EXPERIMENTAL

Materials.—2-Nitrophenazine 10-oxide was prepared according to the literature method,[13] and recrystallized to m.p. 227—228° (from acetic acid). n-Butylamine, t-butylamine, and piperidine (C. Erba pure grade reagents) were purified by recrystallization of their hydrochlorides and repeated distillation from KOH. Triethylamine (C. Erba pure grade reagent) was repeatedly fractionated in the presence of naphthyl isocyanate. Commercial (Merck and C. Erba) spectroscopic grade solvents were used after distillation. 2-Alkylaminophenazine 10-oxides were prepared from 2-chlorophenazine 10-oxide and amines in dimethyl sulphoxide.[5b]

Apparatus.—The u.v. spectra were recorded on a Perkin-Elmer 200 spectrophotometer. Absorbance and fluorescence measurements were obtained on a Beckman DU-2 spectrophotometer and an Aminco–Bowman SPF spectrofluorimeter.

Quantum Yield Determinations.—The samples were prepared immediately before use by mixing the quantities of concentrated solutions of 2-nitrophenazine *N*-oxide and the desired amine so that the resulting solutions were 2×10^{-3}M (MeCN) or 1×10^{-3}M (MeOH) in the *N*-oxide. Tetramethyldiazetine dioxide [14] was added in quenching experiments. Portions (3 ml) were transferred into Pyrex tubes (10 mm i.d.) equipped with lubricated joints and stopcocks and degassed using four freeze–pump–thaw cycles. The samples were irradiated on an optical bench by a super high pressure mercury lamp (Osram HBO 200 W/4) to 5—10% conversion (irradiation time 1—60 min). The 366 nm region of the arc was isolated by using a combination Splinder and Hoyer glass filter (λ_{max} 368 nm, $\Delta\lambda_{1/2}$ 38 nm). The irradiated samples were evaporated at reduced pressure at room temperature under nitrogen. Some toluene was added in order to avoid an increase in the amine concentration during evaporation. The products, previously identified by preparative experiments, were separated by means of column chromatography on 1 cm i.d. columns filled with silica gel (5 g; Merck 70—325 mesh) with cyclohexane–ethyl acetate as eluant (from 9 : 1 to 7 : 3). The solvent was evaporated at reduced pressure and the residue taken up in methanol. 2-Nitrophenazine was determined by absorbance measurements and 2-alkylaminophenazine 10-oxides by fluorescence measurements by comparison with calibration curves. The light intensity was monitored

[10] R. S. Davidson and M. Santhanam, *J.C.S. Perkin II*, 1972, 2355.

[11] R. A. Caldwell, *Tetrahedron Letters*, 1969, 2123.

[12] G. A. Davis, P. A. Carapellucci, K. Szoc, and J. D. Gresser, *J. Amer. Chem. Soc.*, 1969, **91**, 2264.

[13] S. Maffei and G. F. Bettinetti, *Ann. Chim. Italy*, 1955, **45**, 1031.

[14] E. Ullman and P. Singh, *J. Amer. Chem. Soc.*, 1972, **94**, 5077.

by ferrioxalate actinometry.[15] Interference due to thermal reaction was eliminated by comparison with dark experiments performed under the same experimental conditions. Each experiment was repeated at least twice and the mean values were collected in Table 2. Reproducibility was better than 10%. Quenching experiments were always run in parallel with unquenched samples.

Fluorescence Measurements.—Quantum yields were determined relative to quinine sulphate;[16] 10^{-5}M solutions of

2-nitrophenazine N-oxide were used. The solutions were irradiated at 380 nm. The emission maxima were 550 in MeCN and 570 nm in MeOH. Fluorescence quenching by amines was measured under the same conditions.

Treatment of Data.—Slopes of Stern–Volmer plots for quenching and reaction were obtained by a computer least-squares treatment; correlation coefficients were 0.995 or higher for fluorescence quenching.

[15] L. C. Hatchard and C. A. Parker, *Proc. Roy. Soc.*, 1956, **A253**, 318.
[16] W. H. Melhuish, *J. Phys. Chem.*, 1961, **65**, 229.