

Gary A. Epling\* and Kuei-Ying Lin

Department of Chemistry, University of Connecticut,  
Storrs, CT 06268

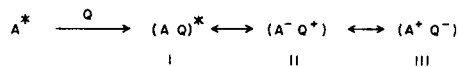
Received January 11, 1984

The efficient fluorescence of 2-phenylquinoline compounds is readily quenched by heteroatom-containing compounds such as amines and sulfides. The mechanism of quenching involves the formation of an exciplex between the quencher and the quinoline; in a few cases a new, red-shifted emission from the exciplex was observed. The efficiency of quenching depends on the ionization potential of the quencher - the compounds having low ionization potentials quench the fluorescence at a diffusion-controlled rate.

*J. Heterocyclic Chem.*, **21**, 1205 (1984).

### Introduction.

In recent years the quenching of the fluorescence of aromatic compounds by formation of an exciplex (heteroexcimer) with amines has been well documented [1]. This quenching may be represented as involving the formation of an intermediate having several resonance contributors, though a charge-transfer contributor, II, is frequently dominant. Though such quenching is common with aromatic



hydrocarbons, it is far less common with heterocyclic aromatics. Exceptions include Gant's observation [2] of excimer formation with quinoline at low temperatures, and Okutsu's detection [3] of the quenching of acridine fluorescence by amines.

We have observed [4] an unusually efficient photofragmentation of some dialkylamino-2-phenylquinolinemethanol antimalarial compounds, **1**, a process which is apparently responsible for their accompanying side effect of phototoxicity [5]. Several factors led us to suspect the involvement of an intramolecular exciplex between side chain amino group and the aromatic nucleus. Accordingly, we initiated a study to probe whether exciplex formation with such compounds is unusually efficient. We have examined several parent 2-phenylquinolinemethanol compounds, **2**, and found that they readily form exciplexes with a wide variety of other compounds which contain sulfur or nitrogen.

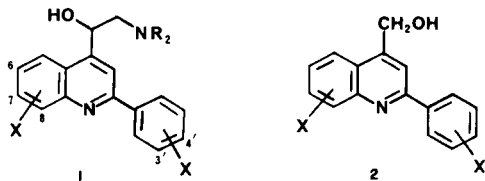


Table 1

Quantum Efficiency of Fluorescence of Representative 2-Phenylquinolinemethanols		
Compound	Substituents	$\phi_f$
<b>2a</b>	6-OCH <sub>3</sub> , 4'-CH <sub>3</sub>	0.12
<b>2b</b>	6-OCH <sub>3</sub> , 3'-Cl, 4'-Cl	0.095
<b>2c</b>	6-Cl, 8-Cl, 3'-Cl, 4'-Cl	0.062

### Results.

The fluorescence of the 2-phenylquinolinemethanol compounds, **2**, was generally efficient, with a quantum efficiency of fluorescence of about 0.1, and a  $\lambda$  max of emission near 395 nm in methanol. Representative values for the efficiency of emission are shown in Table 1.

As expected, the addition of chloro substituents causes a decrease in the efficiency of fluorescence, with the lowest efficiency seen with the tetrachloro compound, **2c**, an intermediate value for the dichloro derivative, **2b**, and the highest value for the non-chlorinated compound, **2a**. The graph of intensity of emission *vs.* concentration of **2** was linear at very low concentrations of **2** (*ca.* 10<sup>-4</sup> M) and showed the expected curvature at higher concentrations as the optical density of the solution began to be so high that all the incident light was being captured. At concentrations exceeding 10<sup>-3</sup> M the intensity of emission in some cases actually declined, which we now attribute to the formation of excimers between excited **2** and a ground state **2** - an additional deactivation mechanism for excited **2** which "wastes" photons.

The  $\lambda$  max of emission was at longer wavelengths in more polar solvents (red-shifted) suggesting that the configuration of the emitting state was  $\pi\pi^*$ .

The addition of triethylamine, perhaps the most commonly used "donor" for exciplex formation with aromatic hydrocarbons, led to quenching of the fluorescence of all the compounds examined. Similarly, other amines, sulfides, disulfides, and some heterocyclic compounds were also found to quench the fluorescence of **2**, though higher

concentrations of some of these materials were required for efficient quenching.

The concentration dependence of the quenching of fluorescence, whether by energy transfer or by exciplex formation, is expected to follow the behavior predicted by the Stern-Volmer equation.

$$\phi_0/\phi_f = 1 + k_Q\tau[Q]$$

In general, we observed the quenching closely followed the expected behavior, as can be seen by Figure 1, which illustrates the quenching of **2c** by isopropyl disulfide, **3**.

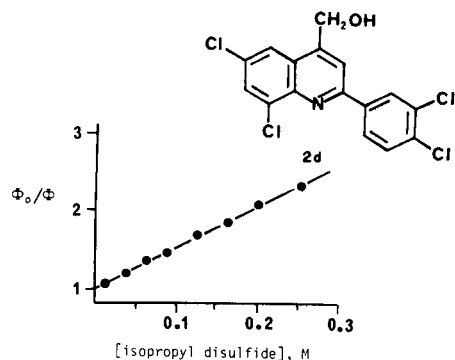


Figure 1. Quenching of the fluorescence of **2c** by isopropyl disulfide, **3**.

From the slope of the Stern-Volmer plot one directly obtains the value of  $k_Q\tau$ . Since the value of  $k_Q$  is a direct measure of the efficiency of the quenching interaction, we proceeded to determine the value of the lifetime,  $\tau$ , of the emitting species. Direct measurement of the luminescence lifetime gave values of  $1.58 \times 10^{-9}$  sec for **2a**,  $1.30 \times 10^{-9}$  sec for **2b**, and  $1.86 \times 10^{-9}$  sec for **2c**. These values were close to, but about 2 to 4 times longer than the approximate values predicted using the integrated extinction co-

efficient. Thus, we felt we could proceed with confidence to determine the actual values for  $k_Q$  with various quenchers. These values are shown in Table 2, and graphically in Figure 2.

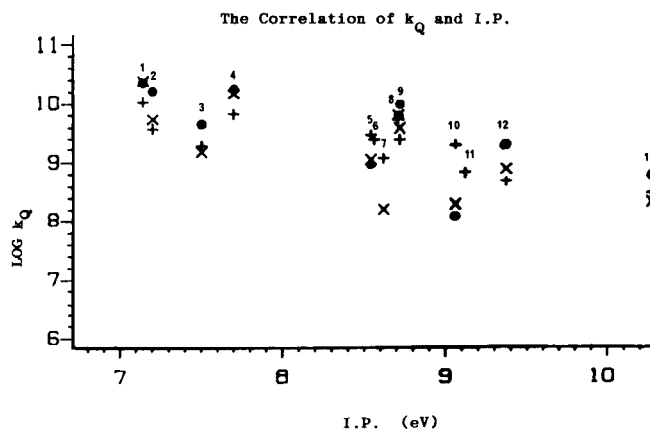


Figure 2. Correlation of  $k_Q$  and ionization potential of the quenchers; x, quenching of **2a**; ●, quenching of **2b**, +, quenching of **2c**.

In a few cases the quenching of the fluorescence was accompanied by the formation of a new emission (see Figure 3). This emission was generally broad, red-shifted, and structureless, and was attributed to emission from the exciplex of the quencher plus **2**. While it is common for exciplexes *not* to fluoresce, there are many examples in which such emission from exciplexes of aromatic hydrocarbons has been observed [12].

#### Discussion.

The most striking initial observation is that the quenching of the fluorescence of **2** by the exciplex-forming quenchers is extremely efficient. The most efficient quenchers quench at rates which are essentially diffusion-controlled

Table 2  
Rate of Quenching of the Fluorescence of **2**

Quencher	Point #	IP quencher	<b>2a</b>	<b>2b</b>	<b>2c</b>
<i>N,N</i> -Dimethylaniline	1	7.14 [d]	10.38	10.35	10.04
DABCO	2	7.20 [e]	9.72	10.20	9.56
Triethylamine	3	7.50 [d]	9.17	9.65	9.28
Aniline	4	7.70 [c]	10.14	10.24	9.83
Isopropyl Disulfide	5	8.54 [a]	9.04	8.96	9.46
2-Ethylthiophene	6	8.56 [a]	x	x	9.38
Isopropyl Sulfide	7	8.62 [a]	8.19	x	9.06
Pyridazine	8	8.71 [f]	9.79	9.78	9.73
Thiomorpholine	9	8.72 [a]	9.56	9.99	9.38
2-Chlorothiophene	10	9.06 [b]	8.28	8.07	9.28
Thiophene	11	9.12 [b]	x	x	8.81
Piperidine	12	9.37 [a]	8.88	9.29	8.68
4-Methylthiazole	13	10.27 [a]	8.30	8.75	8.46

[a] Experimental data, electron impact. [b] Ref [7]. [c] Ref [8]. [d] Ref [9]. [e] Ref [10]. [f] Ref [11], x, not determined.

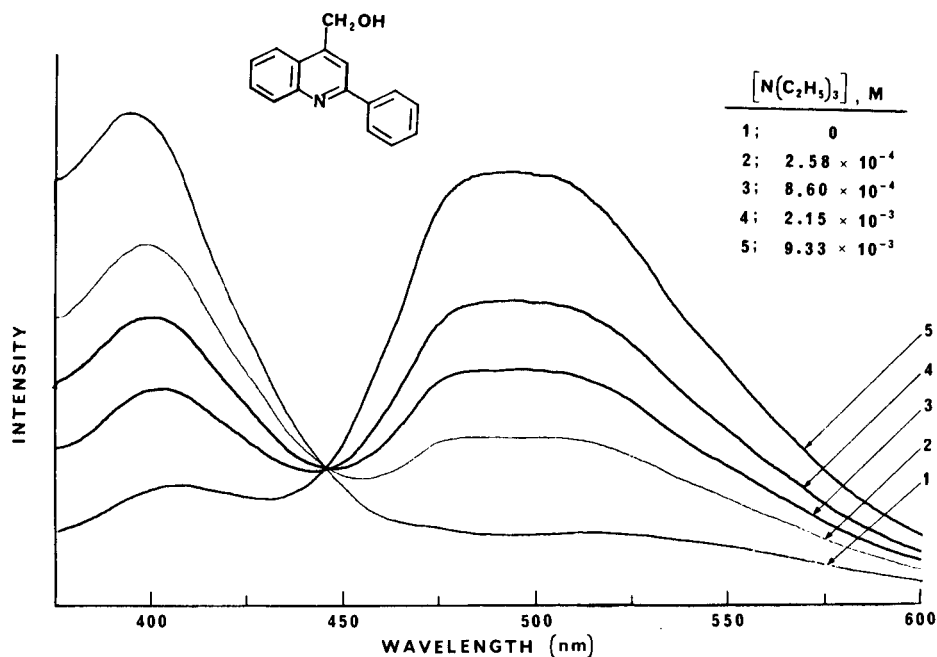


Figure 3. Exciplex emission upon quenching of fluorescence of **2d** with triethylamine.

(calculated as  $1.2 \times 10^{10}$  in methanol). The rate of quenching does decrease as the ionization potential of the quencher increases, the behavior expected for an interaction in which some charge-transfer character becomes important. However, the diminution of  $k_Q$  with the increase of I.P. is less than one might anticipate. A calculation of the slope of a line using *all* points in Figure 2 gives a value of  $-0.62$  (correlation coefficient of 0.720). This value is smaller than that observed for the exciplex quenching of many other aromatic compounds [13,14], indicating that the degree of importance of the charge-transfer contributor of the exciplex (*i.e.* II) is less than in other cases. Alternatively, the formation of the exciplex may be more thermodynamically favored in this case, because there appears to be a difference in the three compounds in their need for a donor of low ionization potential. If one calculates a slope for each compound individually from Figure 2, one finds a slope of  $-0.81$  (correlation coefficient of 0.886) for **2a**,  $-0.65$  (correlation coefficient of 0.787) for **7b**, and  $-0.40$  (correlation coefficient of 0.404) for **2c**. Thus, the most electron-poor aromatic system, **2c**, shows less change with variation in the ionization potential of the quencher. Further, the poor correlation coefficients, particularly with **2c**, indicate that other factors play an important role in determining the efficiency of quenching in addition to electronic factors. Steric factors and the existence of other  $\pi$  systems in the quencher are certain to be considerations as well.

Another factor which is apparently important in determining the efficiency of the quenching, as measured by  $k_Q$ , is the solvent. For example, the  $k_Q$  for quenching of **2b** by piperidine increased from  $1.61 \times 10^{10}$  to  $2.09 \times 10^{10}$  by changing the solvent from benzene to the more polar acetonitrile. However, the change in  $k_Q$  was not dramatic considering the great difference in polarity of the two solvents. The most dramatic change was observed in hydrogen-bonding solvents, such as methanol, which tended to *decrease* the observed  $k_Q$ . For example, the quenching of fluorescence of **2a** by piperidine proceeded with a  $k_Q$  of  $3.9 \times 10^9$  in benzene, but dropped to  $7.9 \times 10^8$  in methanol. The hydrogen-bonding solvents apparently are making the unshared electrons in the "quencher" less available (due to the hydrogen bonding) than one might anticipate on the basis of gas phase ionization potentials. Thus, quenchers which are expected to be less hydrogen-bonded to the solvent, *e.g.* 2-ethylthiophene, actually showed an *increase* in the value of  $k_Q$  in methanol rather than a decrease. For example, the quenching of **2c** by 2-ethylthiophene in benzene showed a  $k_Q$  of  $6.4 \times 10^8$  and a value of  $2.4 \times 10^9$  in methanol. The overshadowing of the effect of the polarity of the solvent by its hydrogen-bonding ability also suggest the formation of an exciplex which does not have a complete charge-transfer character.

#### Conclusion.

We see that these substituted quinolines, which appa-

rently have lowest  $\pi\pi^*$  excited states, can readily form exciplexes with compounds of low ionization potential. As Gant has pointed out [2], the failure to detect exciplex formation from *N*-heterocycles in the past may be in part due to the absence of measurable fluorescence when the lowest excited state is  $n\pi^*$ . The apparent ease of exciplex formation that we observe in this system suggests that exciplexes may indeed be plausible intermediates encountered during photoreaction of quinoline compounds.

## EXPERIMENTAL

### Materials.

The 2-aryl-4-quinolinemethanols (**2**) were prepared as previously described [4,15,16] from the lithium aluminum hydride reduction of the corresponding cincophens. They were carefully purified by silica gel chromatography, then recrystallization from methanol/methylene chloride. Methanol used was Baker Photrex grade, which was fractionally distilled prior to use. Benzene was Baker Reagent grade, purified by distillation and drying over molecular sieves. Acetonitrile, Baker Photrex grade, was used without further purification. DABCO (1,4-diazabicyclo[2.2.2]octane), Baker, was purified by sublimation. Piperidine, Matheson Coleman and Bell, was purified by distillation. The other quenchers were from Aldrich, and were generally purified by distillation or vacuum distillation.

### Fluorescence Measurements.

Spectra were obtained at room temperature, using a Spex Fluorolog Spectrofluorometer. The excitation was at the  $\lambda$  max of the excitation spectrum, with detection at right angles to excitation. Excitation and emission band-pass values were 10 nm. Concentration of **2** was ca.  $10^{-3}$  M.

Quantum yields of fluorescence were performed on dilute solutions (ca.  $10^{-6}$  M) in methanol at room temperature. The optical density was measured using a Cary 17D spectrophotometer. Fluorescence spectra were taken by excitation at 251 nm. Perylene was used as the standard, using a value of 0.94 [17] as the quantum yield of its fluorescence.

### Ionization Potentials.

For some quenchers values of the ionization potential by electron impact were unavailable. For these a value was obtained using an experimental procedure similar to that described by Thode [18]. An AEI MS-902 Mass Spectrometer was configured with two tandem spectrometers at 90°. Two gases are admitted to the instrument simultaneously, the unknown plus argon (as a standard). Ion current densities were measured for the argon. The ionization potential was determined by extrapolation of the linear portion of the curve using the method of Vought [19] and Koffel and Lad [20].

### Fluorescence Lifetimes.

The lifetime of fluorescence was measured using a PRA Model 3000

system, consisting of a hydrogen arc lamp, excitation filter, monochromer emission, and photomultiplier tube. A PDP 1103 computer was used for deconvolution of the lamp profile from the sample decay and calculation of the luminescence lifetime from the decay curve, using the Decay V2.3 program supplied by PRA.

### Acknowledgements.

We are grateful to the National Institutes of Health and the University of Connecticut Research Foundation for financial support of this work. We further thank Mr. Dimitrios Psaras and Dr. Steven Suib for assistance in the determination of the fluorescence lifetimes.

## REFERENCES AND NOTES

- [1] "The Exciplex", M. Gordon and W. R. Ware, eds, Academic Press, New York, 1975.
- [2] R. P. Blaunstein and R. S. Gant, *Photochem. Photobiol.*, **18**, 347 (1973).
- [3] K. Okutsu and M. Kobayashi, *Josai Shika Daigaku Kiyō*, **8**, 215 (1979).
- [4] G. A. Epling, U. C. Yoon and N. K. N. Ayengar, *Photochem. Photobiol.*, **39**, 469 (1984).
- [5] W. E. Rothe and D. P. Jacobus, *J. Med. Chem.*, **11**, 366 (1967).
- [6] I. B. Berlman, "Handbook of Fluorescence Spectra of Aromatic Molecules", 2nd Ed, Academic Press, New York, 1971, pp 54-57.
- [7] S. Pignataro, L. Paolo and G. Marino, *Ric. Sci.*, **39**, 668 (1969).
- [8] K. Watanabe and J. R. Mottl, *J. Phys. Letters*, **26**, 1773 (1957).
- [9] J. L. Franklin, J. G. Dillard, H. M. Rosenstock, J. T. Hesson, K. Dravel and F. H. Field, "Ionization Potentials, Appearance Potentials and Heats of Formation of Gaseous Positive Ions", National Bureau of Standards, 1969.
- [10] A. M. Halpern, J. L. Roebber and K. Weiss, *J. Chem. Phys.*, **49**, 1348 (1968).
- [11] A. J. Yench and M. A. El-Sayed, *J. Chem. Phys.*, **48**, 3469 (1968).
- [12] N. Mataga and M. Ottolenghi, "Photophysical Aspects of Exciplexes", in "Molecular Association", Vol 2, R. Foster, ed, Academic Press, London, 1979, pp 1-78.
- [13] J. B. Guttenplan and S. G. Cohen, *J. Am. Chem. Soc.*, **94**, 4040 (1972).
- [14] J. B. Guttenplan and S. G. Cohen, *Tetrahedron Letters*, 2163 (1972).
- [15] G. A. Epling and M. E. Walker, *ibid.*, 3843 (1982).
- [16] G. A. Epling, N. K. N. Ayengar, A. Lopes and U. C. Yoon, *J. Org. Chem.*, **43**, 2928 (1978).
- [17] W. R. Dawson and M. W. Windsor, *J. Phys. Chem.*, **72**, 3251 (1968).
- [18] R. L. Graham, A. L. Harkness and H. G. Thode, *J. Sci. Instr.*, **24**, 119 (1947).
- [19] R. H. Vought, *Phys. Rev.*, **71**, 93 (1947).
- [20] M. B. Koffel and R. A. Lad, *J. Chem. Phys.*, **16**, 420 (1948).