

Structural Requirements for Efficient Photoinduced Electron Transfer (PET) Quenching in 9-Aminoalkylanthracenes

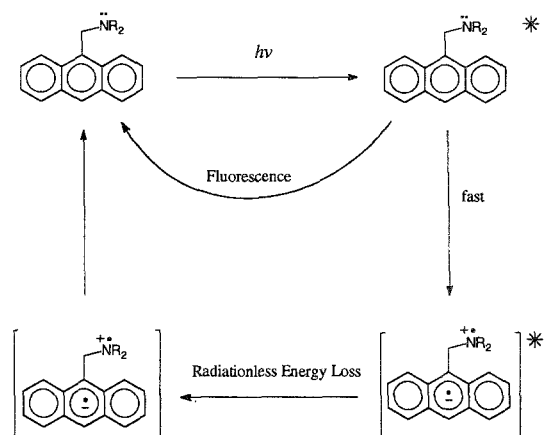
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The structure-quenching relationship in 9-aminoalkylanthracenes is examined by the synthesis and fluorescence evaluation of five derivatives; it is observed that benzylic 2° and 3° amines lead to $\geq 95\%$ quenching of anthracene fluorescence in water, while other amines afford substantially lower quenching efficiencies.

KEY WORDS: Photo induced electron transfer (PET) quenching; 9-aminoalkylanthracenes; structure.

Since the first reports of rationally designed fluorescent chemosensors by Sousa and Larson [1], a variety of binding and signal transduction schemes has been described coupling the two phenomena [2]. One extensively utilized technique involves the inhibition of photoinduced electron transfer (PET) quenching in aminoalkylaromatic hydrocarbons [3]. In this scheme (Scheme I), the initial fluorescence of anthracene is quenched intramolecularly by the amine group. Interest in PET quenching began with the observation of exciplex formation in the early 1960s [4]. Many quenching events involving electron transfer correlate with the redox potentials of the donor-acceptor pair. To predict the feasibility of electron transfer, one must consider the free energy change associated with this transfer. Rehm and Weller [5] derived a kinetic relationship for the redox potential differences to evaluate the ability of PET quenching to compete with other relaxation phenomena. Comparisons of the reduction potential of the acceptor and oxidation potential of the donor can be used to determine the free energy change and rate of transfer. One



Scheme I. Proposed mechanism of PET quenching for a 9-aminoalkylanthracene.

can assume that electron transfer will be relatively fast if this difference in redox potentials is ≥ 0 V ($\Delta G^0 \leq 0$ kcal/mol and $k_q \sim$ diffusion controlled) [6].

Any interaction requiring Lewis base coordination of the amine lone pair (e.g., protonation, metal chelation, complexation to cations) decreases its ability to

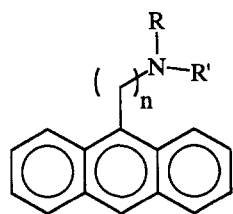
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quench fluorescence via **PET**, resulting in an observed chelation-enhanced fluorescence (**CHEF**). Inherent in such intensometric signaling is a requirement for efficient intramolecular quenching of the noncomplexed chemosensor [7]. Relevant work on the geometric requirements for exciplex formation in aminoalkylnaphthalenes has been reported by Chandross and Thomas [8] and by Davidson and co-workers [3a,d,9] which reveals that benzylic amines are uniquely positioned for efficient **PET**. While a similar effect has been reported for 9-*N,N*-diethylaminomethylanthracene [3a], a 3° benzylic amine, a systematic structure-quenching relationship for anthracene has not been described heretofore. Knowledge of this relationship would be useful in the design of **CHEF** chemosensors relying on intramolecular amine **PET**, given that the greatest signal range will result from sensors with the lowest initial fluorescence. We report here the synthesis and evaluation of several anthracene derivatives relevant to this issue.

To evaluate this effect, 9-aminomethylanthracenes **1–3** (Fig. 1) were prepared. Primary amine **1** was made by use of the Mitsunobu reaction [10], starting with 9-anthracenemethanol, in a 35% overall yield. Compound **2** was purchased from Aldrich Chemical Co. and used without further purification. Substitution of 9-chloromethylanthracene with dimethylamine followed by extraction and crystallization from isopropyl alcohol afforded compound **3**. Compounds **1** and **3** gave satisfactory ¹H NMR, ¹³C NMR, and high-resolution mass spectra. The purity of compound **2** was confirmed by ¹H and ¹³C NMR spectroscopy.

The fluorescence quenching behavior of these amines was evaluated by examination of their pH-fluorescence profiles as shown in Fig. 2. The fluorescence emission



- 1: R = R' = H; n = 1
 2: R = CH₃, R' = H; n = 1
 3: R = R' = CH₃; n = 1
 4: R = R' = CH₃; n = 2
 5: R = R' = CH₃; n = 3

Fig. 1.

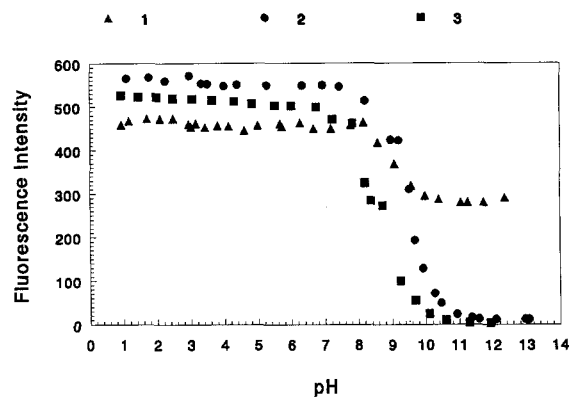


Fig. 2. pH-fluorescence profiles for compounds **1–3**.

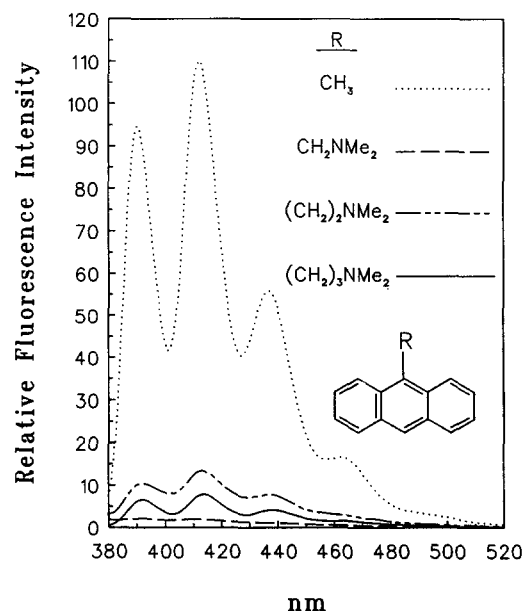


Fig. 3. Fluorescence behavior of 9-methylanthracene and compounds **3–5** in acetonitrile.

was monitored at 416 nm after excitation at 364 nm (absorbance maximum).³ The pH of each aqueous 10 μ M anthracene solution was adjusted by the addition of concentrated HCl or a saturated NaOH solution. Compound **1** shows only 40% quenching, while compounds **2** and **3** show a 47- and 122-fold decrease in fluorescence intensity. The fluorimetrically determined pK_a 's are as

³ Fluorescence measurements were made on a Perkin-Elmer LS-5 luminescence spectrometer; both emission and excitation slit widths were 10 nm.

Table I. Redox Potentials for Compounds 1–3

Compound	Amine E_p (V)	Anthracene E_p (V) ^a	$E_{A^*/A^-} - E_{D/D^+}$ (V)	$k_q \times 10^{-9}$ ($M^{-1} s^{-1}$) ^b
1	1.55 ^c	1.32	-0.23	0.0004
2	1.39 ^d	1.32	-0.07	0.266
3	1.05 ^d	1.32	+0.27	10.03

^aFrom Ref. 6.

^bCalculated using Eqs. 12 and 13 from Ref. 5. It is important to note that these are calculated second-order rate constants for intermolecular quenching. Compounds 1–5 show intramolecular quenching. The amine donor and the anthracene excited-state acceptor were treated as separate moieties in calculating the rate constants. No effort is made here to predict the effective amine molarities that would be necessary to compare first-order rate constants.

$$\text{Equation 12: } \Delta G_{ET}^\ddagger = \left[\left(\frac{\Delta G_{ET}}{2} \right)^2 + (\Delta G_{ET}^\ddagger(0))^2 \right]^{1/2} + \frac{\Delta G_{ET}^\ddagger}{2}$$

$$\text{Equation 13: } k_q = \frac{20 \times 10^9 M^{-1} s^{-1}}{1 + 0.25 \left[\exp\left(\frac{\Delta G_{ET}^\ddagger}{RT}\right) + \exp\left(\frac{\Delta G_{ET}}{RT}\right) \right]}$$

^cFrom Ref. 12.

^dFrom Ref. 13.

follows: **1**, 8.5; **2**, 9.5; and **3**, 8.6.⁴ Note that the pK_a 's are uniformly lower than those of nonbenzylic reference amines (methylamine, 10.6; dimethylamine, 10.8, trimethylamine, 9.8).

The oxidation potentials for compounds 1–3 were estimated from their related benzylic amine derivatives and are presented in Table I along with the reduction potential for the excited state of anthracene. Using the empirical equation proposed by Rehm and Weller [5] based on the Stern–Volmer relationship and steady-state approximation, we are able to calculate expected second-order rate constants to aid in the comparison of intramolecular quenching by these PET processes. For anthracene, the excited-state lifetime in polar solvents is ~5 ns [11]. For quenching to occur, the rate of electron transfer must occur during this lifetime. The calculated rate constants for quenching indicate that compound **3** should quench, while compound **1** is expected to show less quenching. Compound **2** is potentially a quencher but may not completely quench. Examination of Fig. 2 shows that the fluorescence quenching behavior for the secondary and tertiary amines was as expected (i.e., fluorescence quenched), and the primary amine displayed lower quenching.

In addition to the thermodynamic considerations for

PET quenching, we examined the importance of proximity between donor and acceptor by evaluation of the fluorescence behavior of compounds 3–5. Compounds **4** and **5** were synthesized by halogen–metal exchange of 9-bromoanthracene to form 9-lithioanthracene. The addition of ethylene oxide or trimethylene oxide followed by the addition of water afforded the appropriate alcohol precursor. Conversion of the alcohols to the bromo derivatives was done with phosphorous tribromide. Substitution of the bromine with dimethylamine was performed at room temperature to afford the desired products.⁵

Fluorescence spectra of 10 μM acetonitrile solutions of 9-methylanthracene and compounds 3–5 were obtained from 380 to 520 nm (Fig. 3).⁶ Compounds **4** and **5** experience a 6.6- and 11-fold quenching of fluorescence compared to 9-methyl anthracene. Compound **3**, containing the benzylic amine moiety, experiences a substantially larger quenching effect (48-fold). The residual intensity shown in Fig. 3 may be due only to background emission and scattering. Davidson and co-workers [3a,d,9] have postulated that long tethers between donor and acceptor molecules result in a number

⁵ Compounds **4** and **5**, as well as all synthetic intermediates gave suitable NMR spectra.

⁶ Fluorescence measurements were made on a Perkin–Elmer LS-5 luminescence spectrometer; both emission and excitation slit widths were 3 nm. Excitation was at 335 nm.

⁴ Determined by plotting with the program ENZFITTER (Elsevier-BIOSOFT, 68 Hills Road, Cambridge CB2 1LA, UK).

of ground-state configurations where the donor is not sufficiently near the acceptor, so that on excitation, several bond rotations must occur to allow proper alignment for electron transfer. Additionally, they postulate that the efficient quenching for the benzylic case may be a result of through bond interactions via the C–H bonds of the methylene spacer. Weller and associates' [3e] work with 2-anthracene carboxylic ester alkyldimethylamine indicated that PET is important and can occur over long tether lengths (up to 14 atoms). Our results confirm these conclusions by exhibiting quenching in all three cases, but the effectiveness of the quenching event decreases as the donor becomes more distal.

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