Enhanced Basicity of the 2-Position of 1,3-Dialkoxybenzenes in S_1: Acid Catalyzed Photochemical Proton/Deuteron Exchange

Renée Mosi, Guangzhong Zhang, and Peter Wan*

Department of Chemistry, University of Victoria, Box 3055, Victoria, British Columbia, Canada V8W 3P6

Received July 6, 1994[⊗]

The photochemistry of several 1,3-dialkoxy-substituted benzenes **1−8** has been studied in aqueous H_2SO_4 (D_2SO_4) solution. In contrast to ground state behavior, all of these compounds (with the exception of **7**) are photoprotonated efficiently (via S_1) and almost exclusively at the 2-position (and to a much lesser extent at the 5-position) to give dialkoxy-substituted cyclohexadienyl cation intermediates (2,6-dialkoxybenzenonium ions), resulting in proton/deuteron exchange of the 2-position of the benzene ring for all systems except **4** (and **7**). In the ground state, protonation takes place predominantly at the 4-position for **1−4** and at the 6-position for **5** and **6**. In the case of **4**, photoprotonation at the 2-position is implicated by observation of fluorescence quenching by acid but deuterium exchange at this position is not possible. Photoprotonation (quenching) rate constants (k_H) were calculated by Stern−Volmer analysis of steady state fluorescence quenching by proton and are in the range $0.9-3 \times 10^9$ M^{-1} s^{-1}. Quantum yields for deuterium incorporation in 4:1 aqueous $D_2SO_4-CH_3CN$ are reported for several substrates at selected acidities. The sigmoid dependence of plots of fluorescence quenching vs acidity is used to give estimated $pK_{BH^+}^*$ of $\approx 0.1-0.5$ for these substrates, indicating that they are much more basic in S_1 than in S_0.

Introduction

It is well known that many organic molecules exhibit substantial changes in acid−base strength on electronic excitation.[1] The utility of such behavior in organic photochemistry has been reviewed.[1c] Of recent interest in our group is the change (enhancement) of basicity of aromatic rings on electronic excitation. The protonation/deprotonation of aromatic systems is regarded as the simplest of all electrophilic aromatic substitution reactions. In addition, the reaction may be viewed as an acid−base equilibrium in which the neutral aromatic system acts as the conjugate base. Such aromatic systems in the ground state are in general very weak bases ($pK_{BH^+} \ll 0$).[2] Literature reports of the facile *photo*protonation of substituted benzenes[1c,3,4] as well as other aromatic systems[1c,3a,4] have appeared throughout the last three decades, with quantitative studies appearing in only recent years. We recently reported that 1,2-dimethoxybenzene (veratrole) and related compounds undergo acid-catalyzed photochemical *ipso* substitution of the alkoxy group by H_2O in aqueous H_2SO_4.[5] On the other hand, the isomeric 1,3- and 1,4-dimethoxybenzenes showed no tendency to react via this pathway but deuterium was incorporated (regioselectively at the 2-position for 1,3-dimethoxybenzene (**1**)) on the aromatic ring when these compounds were photolyzed in aqueous D_2SO_4, indicating that *photoprotonation* was taking place for all substrates, although with different efficiencies.[5b] McClelland and co-workers[6] have also reported the facile photoprotonation of a number of substituted benzenes in 1,1,1,3,3,3-hexafluoro-2-propanol (HFP), in particular, the regioselective photoprotonation of 1,3-dimethoxybenzenes and related compounds at the 2-position. Laser flash photolysis (LFP) studies[6] provided kinetic data for decay of the photogenerated cyclohexadienyl cations (benzenonium ions) in HFP. We now report a study of the photoprotonation of a series of 1,3-dialkoxy-substituted benzenes, adding more insights into our understanding of this simple photochemical process. Quantum yields for exchange (deuterium incorporation) and rates for photoprotonation are reported for a number of substrates, which provide a measure of reactivity of the singlet excited state responsible for the photoprotonation, data which complements those derived from LFP studies.[6]

Results and Discussion

Product Studies. The substrates studied (**1−8**) were commercially available except for **2, 3,** and **8;** compounds **2** and **3** were readily made via standard alkylation methodologies starting from resorcinol while **8** was made via quenching of the 2-lithio derivative of **2** with D_2O. Results for **1** have been reported elsewhere[5b] and are

[⊗] Abstract published in *Advance ACS Abstracts,* November 15, 1994.

(1) (a) Ireland, J. F.; Wyatt, P. A. H. *Adv. Phys. Org. Chem.* **1976,** *12,* 131. (b) Vander Donckt, E. *Prog. React. Kinet.* **1970,** *5,* 273. (c) Wan, P.; Shukla, D. *Chem. Rev.* **1993,** *93,* 571.

(2) (a) Liler, M. *Reaction Mechanism in Sulfuric Acid;* Academic Press: London, 1971. (b) Stewart, R. *The Proton: Applications to Organic Chemistry;* Academic Press: Orlando, 1985.

(3) (a) Cornelisse, J.; Havinga, E. *Chem. Rev.* **1975,** *75,* 353. (b) de Bie, D. A.; Havinga, E. *Tetrahedron* **1965,** *21,* 2395. (c) Lodder, G.; Havinga, E. *Tetrahedron* **1972,** *28,* 5583. (d) Spillane, W. J. *Tetrahedron* **1975,** *31,* 495. (e) Mason, S. F.; Smith, B. E. *J. Chem. Soc. (A)* **1969,** 325. (f) Smith, B. E. *J. Chem. Soc. A* **1969,** 2673. (g) Kuzmin, M. G.; Uehinov, B. M.; Gyorgy, G. S.; Berezin, I. V. *Russ. J. Phys. Chem. (Engl. Transl.)* **1967,** *41,* 400. (h) Vesley, G. F. *J. Phys. Chem.* **1971,** *75,* 1775. (i) Colpa, J. P.; Maclean, C.; Mackor, E. L. *Tetrahedron, Suppl.* **1963,** *2,* 65. (j) Flurry, R. L., Jr.; Wilson, R. K. *J. Phys. Chem.* **1967,** *71,* 589.

(4) (a) Shizuka, H. *Acc. Chem. Res.* **1985,** *18,* 141. (b) Wan, P.; Zhang, G. *Res. Chem. Intermed.* **1993,** *19,* 119.

(5) (a) Wan, P.; Wu, P. *J. Chem. Soc., Chem. Commun.* **1990,** 822. (b) Pollard, R.; Wu, S.; Zhang, G.; Wan, P. *J. Org. Chem.* **1993,** *58,* 2605.

(6) (a) Mathivanan, N.; Cozens, F.; McClelland, R. A.; Steenken, S. *J. Am. Chem. Soc.* **1992,** *114,* 2198. (b) Steenken, S.; McClelland, R. A. *J. Am. Chem. Soc.* **1990,** *112,* 9648. (c) Lew, C. S. Q.; McClelland, R. A. *J. Am. Chem. Soc.* **1993,** *115,* 11516.

presented here for comparison purposes since it may be regarded as the prototypical system.
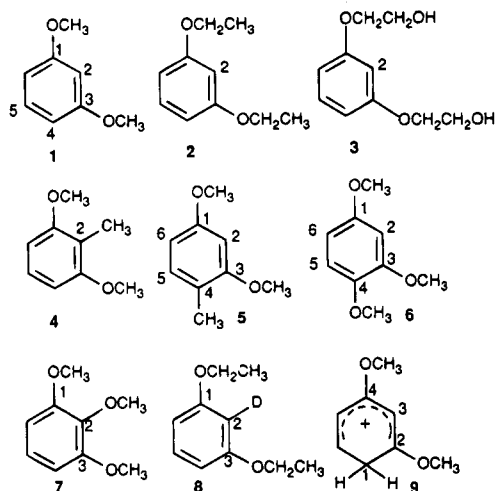
In contrast to 1,2-dialkoxybenzenes, 1,3-dialkoxy-substituted benzenes do not undergo acid-catalyzed photochemical *ipso* substitution by H_2O (to give the corresponding phenols).[5] Thus photolysis of **1–3** (10^{-3} M; Rayonet RPR 100 photochemical reactor; 254 nm lamps; 10–60 min; $\approx$15 °C) in 2:1 H_2O–CH_3CN (acidity of the H_2O portion was varied from pH 7 to $\approx$10% (w/w) H_2SO_4) resulted in no photoproducts (GC and ^{1}H NMR) and the substrates can be recovered unchanged.

Compounds **4–7** have ortho substituents to a methoxy group, raising the possibility that acid-catalyzed *ipso* photosubstitution reaction may be occurring, giving rise to the corresponding phenols, which we reported for several ortho-substituted alkoxy benzenes.[5] Photolysis of **4–7** under conditions that would result in significant ($\approx$30%) deuterium incorporation for **1–3, 5**, and **6** at the 2-position resulted in no observable phenolic products (by GC) formed from substitution of an alkoxy group by H_2O, indicating that either simple photoprotonation–deprotonation at the 2-position[7] (which may or may not lead to exchange, depending on the substrate (*vide infra*)) is the dominant process for these compounds, or they are completely unreactive.

Photolysis of **4** and **7** in 2:1 10% D_2SO_4–CH_3CN (30–60 min) resulted in no observable deuterium incorporation. This would be consistent with photoprotonation of the 2-position as the major pathway of reaction (or else are unreactive) since these compounds have "blocked" 2-positions and even if deuteration were taking place to generate the corresponding cyclohexadienyl cations, one would not expect either the methyl group (of **4**) or the methoxy group (of **7**) to leave with a formal positive charge. For these derivatives, it is most likely that if photoprotonation did occur (*vide infra*), it is entirely reversible.

The photoprotonation of **1–3, 5**, and **6** was studied in 2:1 D_2O–CH_3CN (acidity of the D_2O portion varied from pD 7 to 10% D_2SO_4). For **1–3**, thermal exchange did not become competitive under the above conditions at acidities ≤10% D_2SO_4. A dark reaction of **3** in 30% D_2SO_4 for

5–10 min gave only deuteration at the 4-position. The location of deuterium was deduced by 360 MHz ^{1}H NMR (Figure 1). Whereas H5 of **3** appears as a triplet (δ 7.17, J = 8 Hz) in unreacted material, incorporation of a deuterium at C4 would result in an additional doublet for H5 at the same resonance (couplings to deuterium not resolvable), which was observed. NMR integration gave $\approx$20% monodeuteration in this run. Confirmation of deuteration came from GC/MS, which in general agreed with % deuteration calculated by ^{1}H NMR. This dark run for 60 min resulted in deuteration at both C4 and C2 (majority at C4).

Kresge and co-workers[8] have measured the rates of detritiation of 1,3-dimethoxybenzene-*4-t* and 1,3-dimethoxybenzene-*2-t*, in which the former reacted five times faster and showed that in 95% H_2SO_4, **1** is completely protonated at C4 to give 2,4-dimethoxybenzenonium ion (**9**). Our thermal exchange results for **3** are consistent with the enhanced reactivity of C4 vs C2 of these 1,3-dialkoxy-substituted compounds in the ground state.

Photolysis of **3** in 2:1 10% D_2SO_4–CH_3CN (10 min) gave deuteration regioselectively at the 2-position (Figure 2). Thus the doublet of doublets (δ 6.52, J = 8 and 2.4 Hz) observed for H4 of **3** is superimposed with a doublet (J = 8 Hz; absence of observable coupling to deuterium at the 2-position) due to formation of **10** (eq 1). The triplet
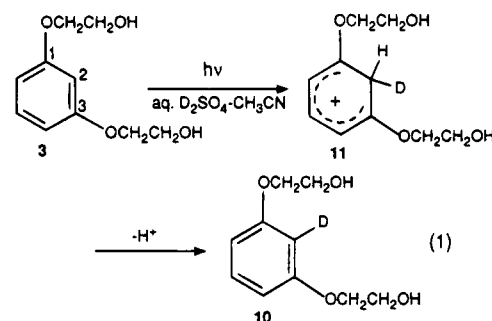
(δ 6.49, J = 2.4 Hz) of H2 decreased in signal intensity due to its replacement by deuterium. No changes were observed for the triplet of H5 consistent with no exchange of H4. Conversion to monodeuterated product was calculated to $\approx$20% by NMR integration. On extended photolysis (1 h), the signal at H2 disappeared completely (complete deuteration of the 2-position). Some dideuterium incorporation was also observed, the second deuterium being at the 5-position since a weak new singlet between the expected doublet (due to monodeuterated product) was observed for H4. Essentially identical results were observed for **2**. Thus formation of the 2,6-dialkoxybenzenonium ion **11** (and to a much lesser extent the 3,5-dialkoxybenzenonium ion) is implicated in these photoprotonations.

To illustrate the efficiency and regioselectivity of the photochemical exchange, 1,3-diethoxybenzene-*2-d* (**8**) was irradiated in 10% H_2SO_4 and the extent of exchange followed by ^{1}H NMR (Figure 3) and plotted as a function of photolysis time (Figure 4). The starting material **8** was made in 93% purity (remainder being **2**). On photolysis, the triplet (J = 2.4 Hz) at δ 6.44 grows in along with a doublet of doublets (J = 8 and 2.4 Hz) due

---

(7) The numbering system used for locating deuterium exchange of the compounds studied may not correspond to the actual numbering system used for naming the compound under IUPAC rules for some compounds. Adopting a numbering system based on the parent 1,3-dimethoxybenzene (**1**)—where the 2-position is adjacent to two methoxy groups—for discussion of exchange simplifies the tracking of the activated position in S_1 (and in S_0) and avoids possible confusion.

(8) (a) Kresge, A. J.; Chiang, Y.; Hakka, L. E. *J. Am. Chem. Soc.* **1971**, *93*, 6167. (b) Kresge, A. J.; Mylonakis, S. G.; Sato, Y.; Vitullo, V. P. *J. Am. Chem. Soc.* **1971**, *93*, 6181.
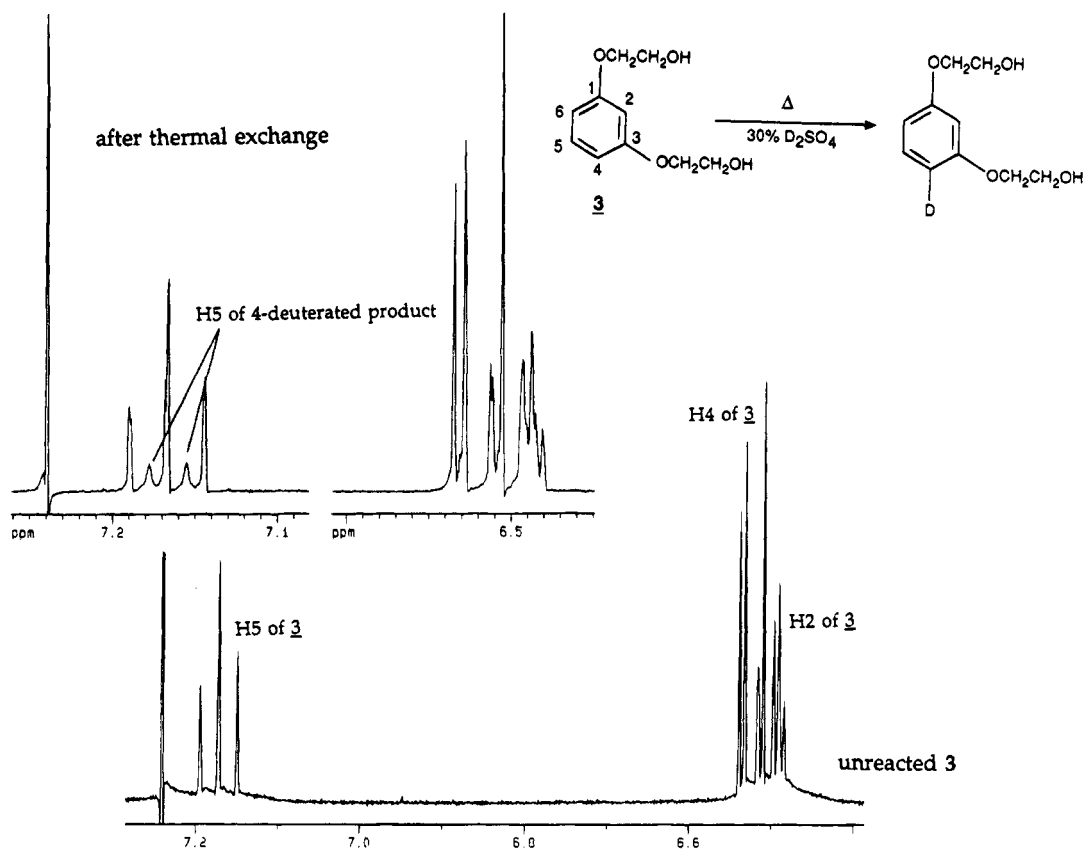
Figure 1. ¹H NMR (360 MHz) spectra (aromatic region) showing exchange of the 4-position of **3** under thermal conditions. Bottom spectrum is unreacted starting material. Top spectrum was taken after reaction with 30% D₂SO₄ for 10 min (note expanded scale used).
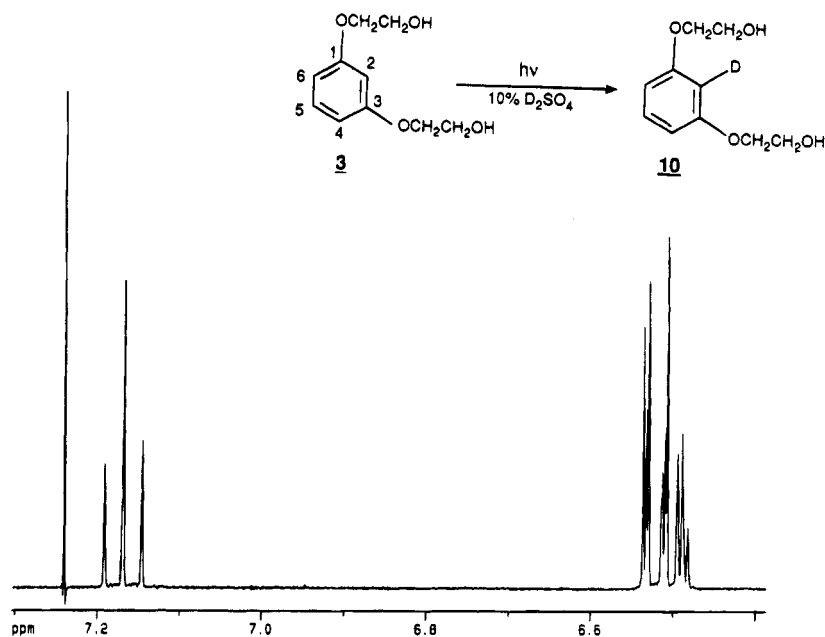

Figure 2. ¹H NMR (360 MHz) spectra (aromatic region) showing exchange of the 2-position of **3** (to give **10**) on photolysis. The spectrum was taken after photolysis in 10% D₂SO₄ for 10 min.

to **3**, superimposed onto the initial doublet of **8** at δ 6.47. No changes were observed for H5 of **8** at δ 7.13, consistent with deuteration exclusively at C2. After 120 min of photolysis, the spectrum is essentially that of **2**. These results show that the exchange can be taken cleanly to very high conversions and hence may be of preparative value because of its simplicity. The thermal method used to carry out such a conversion uses *n*-BuLi (see Experi-

mental Section). Extended photolysis of **8** in 10% D₂SO₄ for 2–3 h resulted in residual deuteration (5–10%) of the 5-position, as indicated by the appearance of a broad unresolved "doublet" ($J \approx 2$ Hz) at δ 6.47 for H4, which in unreacted substrate appears as a resolved doublet ($J = 8$ Hz) due to coupling to H5. The sample was contaminated with thermal exchange at C4 due to the length of the photolysis run.
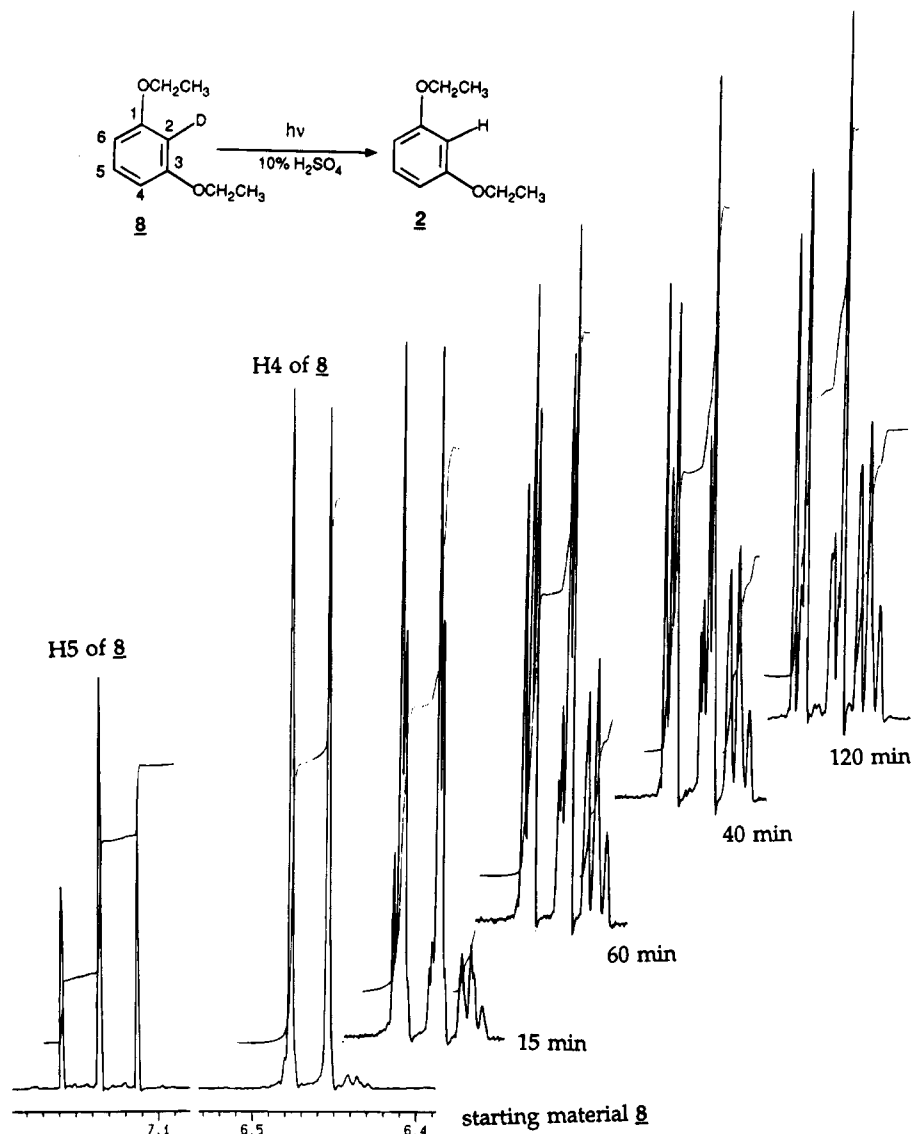
Figure 3. ^{1}H NMR (360 MHz) spectra showing exchange of deuteron by proton at the 2-position of **8** on photolysis in 2:1 10% H_2SO_4–CH_3CN (photolysis times indicated on each spectrum).
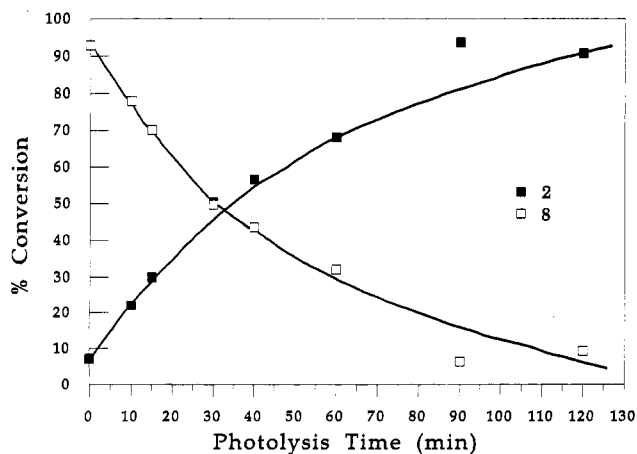

Figure 4. Plot of yield of **2** as a function of photolysis time of **8** in 2:1 5% H_2SO_4–CH_3CN. Substrate **8** was contaminated with 7% of nondeuterated **2**.

Photolysis of **5** and **6** in 2:1 10% D_2SO_4–CH_3CN (30 min) resulted in incorporation of deuterium predominantly at the 2-positions of these compounds (^{1}H NMR assignments given in Experimental Section). Deutera-

tion was also observed at both H5 and H6 of **5** and **6**. Dark control reactions of **5** and **6** showed deuteration (5–10%) at H6 but not at H5. Therefore, the observed exchanges at H5 of **5** and **6** are due to photochemical activation. Photolysis of **5** and **6** at lower acidity (5% D_2SO_4) for 30 min showed much cleaner product mixtures. In these runs, the major products were the corresponding 2-deuterio derivatives with only minor amounts (<5%) of dideuterated products at H5.
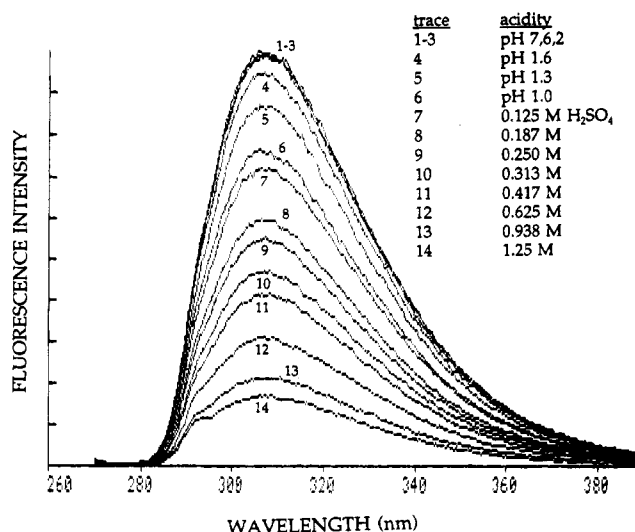
Quantum Yields. Quantum yields (Φ) for formation of the corresponding monodeuterated products of **2, 3, 5,** and **6** were measured as a function of medium acidity (4:1 aqueous D_2SO_4–CH_3CN; $\lambda_{ex} = 254$ nm) using GC/MS and selected ion monitoring on a Kratos Concept H instrument. Conversions were kept <15% which avoided dideuteration. A summary of Φ at various acidities is given in Table 1. The values are very similar to those already reported for 1,3-dimethoxybenzene (**1**).[5b]

In general, Φ was measurable at acidities stronger than $\approx$pD 2 and increases rapidly below pD 1 to give a sigmoid-like dependence. It was not possible to measure Φ at acidities beyond $\approx$10% D_2SO_4 reliably since thermal exchange becomes significant. Therefore, the expected

Table 1. Exchange Quantum Yields (Φ) as a Function of Medium Acidity

| medium acidity[a]- (pD or % D$_2$SO$_4$)	Φ[b]			
	2	3	5	6
pD = 6.9	0.00	0.00	0.00	0.02
pD = 2.5	0.00	0.00	0.026	0.028
pD = 2.0	0.011	0.015	0.033	0.030
pD = 1.5	0.037	0.037	0.050	0.041
pD = 1.2	0.063	0.042	0.069	0.055
pD = 1.0	0.12	0.072	0.10	0.065
pD = 0.79	0.14	0.078	0.15	0.088
pD = 0.48	0.24	0.13	0.22	0.15
5%	0.33	0.14	0.29	0.16
10%	0.34	0.23	0.47	0.25

[a]Solvent system was 4:1 D$_2$O (D$_2$SO$_4$)−CH$_3$CN (pD is of aqueous portion). [b]Measured using GC/MS. Estimated errors ±10% of quoted value.

trace	acidity
1-3	pH 7,6,2
4	pH 1.6
5	pH 1.3
6	pH 1.0
7	0.125 M H$_2$SO$_4$
8	0.187 M
9	0.250 M
10	0.313 M
11	0.417 M
12	0.625 M
13	0.938 M
14	1.25 M

Figure 5. Fluorescence quenching of 2,4-dimethoxytoluene (5) by acid (λ_{ex} = 265 nm).

"plateau" region in the plot could not be verified. However, it would be safe to estimate that the inflection points of these plots are in the region between 1 and 0.

Fluorescence Measurements. Fluorescence emission spectra of 1−7 were measured as a function of medium acidity in wholly aqueous medium using a Perkin-Elmer MPF 66 instrument at sample concentrations $\approx 10^{-4}$ M. With the exception of 7, the fluorescence emission of all compounds were quenched on increasing acidity, as shown in Figure 5 for 5. The fluorescence of these compounds were significantly quenched in a region of acidity where 1,4-dimethoxybenzene and other compounds not known to be photoprotonated efficiently are hardly quenched.[5b] In addition, previous studies of related quenching phenomena[1c] have shown that quenching by acid in this acidity region is completely attributable to the interaction of excited singlet state with proton in a chemical step. It is unlikely that the fluorescence quenching observed here is due to a mechanism not involving protonation of the benzene ring.

Plots of fractional fluorescence quenching vs acidity showed sigmoid-type dependence with inflection points occurring in the region pH = 0.1−0.5. Because of competing thermal exchange at higher acidity, quantum yields (Φ) for exchange were not measured beyond 10% D$_2$SO$_4$ and hence plots of Φ vs acidity showed only the partial sigmoid behavior. However, it is evident in these plots that the "inflection points" are in about the same
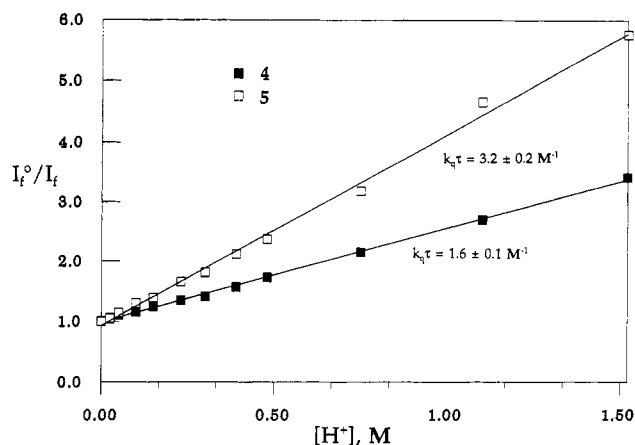
Figure 6. Linear Stern−Volmer plots of fluorescence quenching by proton for compounds 4 and 5.

Table 2. Photoprotonation Rate Constants and Fluorescence Data

compd	τ^a (ns)	Φ_f[b]	$k_H{}^c$ (M^{-1} s^{-1})
1[d]	1.5 ± 0.1	0.14 ± 0.02	(2.2 ± 0.2) × 10^9
2	1.4 ± 0.1	0.14 ± 0.02	(2.6 ± 0.2) × 10^9
3	2.1 ± 0.2	0.14 ± 0.02	(1.4 ± 0.1) × 10^9
4	1.8 ± 0.1	0.11 ± 0.02	(8.8 ± 0.6) × 10^8
5	1.1 ± 0.1	0.13 ± 0.02	(2.9 ± 0.3) × 10^9
6	~0.5	0.067 ± 0.005	~3 × 10^9

[a]Measured by single photon counting in 100% H$_2$O (pH 7 buffer). [b]Measured in 4:1 H$_2$O−CH$_3$CN (pH 7) using 1[5b] as reference. Use of 4:1 H$_2$O−CH$_3$CN (pH 7) gave the same quantum yields, within experimental error. [c]Quenching rate constant (k_q) equated to photoprotonation rate constant (k_H). [d]Values from ref 5b.

acidity region. It was not possible to rank the relative basicity of the compounds studied because of the narrow range of pH in which the inflection points were observed.

Fluorescence quenching observed concurrently with increase in exchange quantum yield (Φ) over the same acidity range strongly indicate that S$_1$ is responsible for the photoprotonation. One cannot rule out a residual triplet pathway. However, triplet reactivity is unlikely since such states have diradicaloid character which would not be expected to have enhanced basicity.

Absolute fluorescence quantum yields (Φ_f) were measured in 4:1 H$_2$O−CH$_3$CN (water portion at pH 7) using 1 as secondary standard (Φ_f = 0.14 ± 0.02).[5b] The results are shown in Table 2. Compound 7 was very weakly fluorescent (Φ_f < 0.01) in H$_2$O-CH$_3$CN, 100% CH$_3$CN, or cyclohexane, and therefore quenching by acid could not be studied with reliability. The fluorescence of the other trimethoxy-substituted system (6) was observable but weaker than any of the dimethoxy-subtituted compounds. The weaker fluorescence emissions of 6 and 7 may be attributable to an enhanced intersystem crossing yield or the existence of a competing radiationless pathway (probably photoionzation since these substrates are more electron rich).

Fluorescence lifetimes of 1−6 ($\approx 10^{-5}$ M) were measured in wholly aqueous solution at pH 7 using single photon counting. The fluorescence emission of 7 was too weak for such a measurement. Good first-order decays were observed for all runs, and the lifetimes are summarized in Table 2.

Fluorescence lifetimes of 1 were also measured in several acid solutions (pH 1.3, 1.0, and 0.80). A Stern−Volmer analysis gave a linear plot, with k_q = (2.6 ± 0.3) × 10^9 M^{-1} s^{-1}, which is in reasonable agreement with

the value obtained from steady-state analysis (Table 2). The fluorescence lifetimes of the other substrates were also shortened in these acid solutions. These observations along with the acid catalysis of deuterium exchange (Table 1) are compelling evidence that the proton interacts directly with the singlet excited state in a primary protonation step and that k_q may be equatable to k_H, the photoprotonation rate constant at the 2-position of these compounds.

Mechanism and Photoprotonation Rate Constants. Although many reports of fluorescence quenching of aromatic compounds have appeared in the literature,[3,4] including evidence that overall proton exchange takes place for some substrates, the photobehavior of simple alkoxy-substituted benzenes has not been fully delineated until recently.[5,6] The results of the present study show the generality of the photoprotonation pathway for many 1,3-dialkoxy-substituted benzenes in aqueous H_2SO_4. In fact, it appears that a 1,3-disubstitution of alkoxy substituents on the benzene ring results in optimal photoprotonation efficiency (at the 2-position) since we have not found compounds that react more efficiently in our studies.

Rate constants for the photoprotonation step (k_H) can now be measured by a simple fluorescence quenching technique (either steady state or using lifetimes). The measured rate constants are in the range $0.9-3 \times 10^9$ $M^{-1} s^{-1}$, being more reactive than 1,2- and 1,4-dimethoxybenzenes ($k_H = 6.0 \times 10^8$ and 9×10^7 $M^{-1} s^{-1}$, respectively).[5b] These very fast rates of protonation of S_1 are due to a substantial increase in basicity of these compounds on electronic excitation, due to electron donation from the two oxygen substituents. We have used simple HMO theory to successfully rationalize the enhanced electron density of the 2- and 5-positions of the benzene ring of these systems.[5b] More sophisticated calculations using a π-SCF PPP method gave similar results.[9] Interestingly, related studies[1c,10] have shown that the most reactive benzyl alcohol toward photodehydroxylation (photosolvolysis) is 2,6-dimethoxybenzyl alcohol, which has the same pattern of methoxy group substitution. This is hardly surprising since the electronic demands for both reactions are identical (electron rich ring carbon atom).

Addition of two hydroxyl groups to the termini of the ethyl groups of **2** (to give **3**) retards the photoprotonation rate by a factor of ≈ 2 whereas the extension of methyl (**1**) to ethyl (**2**) has no measurable effect. The difference in photoprotonation rate constants between **2** and **3** are approximately reflected in the quantum yields (Φ) of deuterium incorporation for these two compounds. The hydroxyl groups of **3** would be expected to be strongly hydrogen bonded to solvent water, which may result in increased steric hindrance for the attacking hydronium ion at the 2-position. The drop in photoprotonation rate (by a factor of ≈ 3) on substitution of a methyl group at the 2-position (in **4**) was expected since this would obviously result in increasing the steric hindrance for the attacking hydronium ion. Using LFP studies in HFP, McClelland and co-workers[6a] have detected the corresponding cyclohexadienyl cation intermediate from **4** as well as for **1** and **5−7**. That is, HFP is sufficiently acidic to photoprotonate these same compounds and is

sufficiently weakly nucleophilic for these cations to be observable in this medium. Unfortunately, we have found that LFP studies of these same compounds in aqueous acid gave only weak signals (≈ 460 nm) assignable to radical cations. It is clear that although these compounds are photoprotonated in aqueous acid, the corresponding cyclohexadienyl cations are too short lived for detection using a nanosecond LFP system.

Substitution of a methyl group at the 4-position (**5**) results in a small enhancement of k_H (compared to **1**) which may be attributable to the electron donating ability of the methyl group. A similar enhancement is also suggested by the introduction of a third methoxy group at the 4-position (**6**) although an accurate calculation of k_H was not posssible due to its short lifetime in pH 7. Although McClelland and co-workers[6b] have confirmed that **7** is also photoprotonated in HFP (by LFP), we were unable to carry out fluorescence quenching studies of this compound due to its very weak emission and therefore unable to show that it is photoprotonated in aqueous acid. One possibility that we have considered is that it is photoprotonated very efficiently, even in neutral pH (i.e., by H_2O), resulting in very short lifetimes in aqueous solution. However, the fact its fluorescence emission is also very weak in 100% CH_3CN and in cyclohexane argues against this latter possibility.

Experimental Section

General. Preparative photolyses were carried out using a Rayonet RPR 100 photochemical reactor equipped with 16 × 254 nm lamps. ¹H NMR spectra were taken in $CDCl_3$ on Perkin-Elmer RS32 (90 MHz), Bruker WM 250 (250 MHz), or AM 360 (360 MHz) instruments. Gas chromatography was carried out on a Varian 3700 instrument with a Hewlett-Packard 3390A integrator using a DB-5 capillary column. Mass spectra were taken on Finnigan 3300 (CI) or Kratos Concept H (EI) instruments. Aqueous acids used for fluorescence and photolysis studies were either commercially available phosphate buffer solutions or freshly made aqueous H_2SO_4 solutions diluted from standardized stock. Aqueous D_2SO_4 solutions were made by diluting commercially available concd D_2SO_4, and the pD values were calculated by the equation[11] pD = pH(meter) + 0.040.

Materials. Compounds **4−7** were purchased from Aldrich and used as received (purity checks indicated that they were >98% pure). Samples which were distilled gave the same fluorescence data. The remaining substrates were prepared via the standard procedures described below.

1,3-Diethoxybenzene (2). To a stirred solution of resorcinol (15 g, 0.14 mol) in 100 mL of acetone were added 25 mL (0.21 mol) of iodoethane and 43.2 g (0.31 mol) of anhydrous K_2CO_3 with stirring. The mixture was gently refluxed for 8 h. It was then diluted with H_2O (500 mL) and extracted with 3 × 50 mL of ether. Evaporation of the ether followed by bulb-to-bulb distillation gave 13.6 g (60%) of **2** as a clear oil: ¹H NMR δ 1.40 (t, $J = 8$ Hz, 6H, CH_3), 4.00 (q, $J = 8$ Hz, 4H, ArOCH_2), 6.45 (t, $J = 2.4$ Hz, 1H, H2), 6.51 (d, $J = 8$ Hz, 2H, H4), 7.15 (t, $J = 8$ Hz, 1H, H5); MS (EI) 166 (M⁺).

1,3-Bis(2′-hydroxyethoxy)benzene (3). This compound was prepared via LiAlH₄ reduction of the diester obtained from standard alkylation of resorcinol with 2-bromoethyl acetate in the presence of K_2CO_3. Resorcinol (30.0 g, 0.27 mol) and ethyl bromoacetate (136.5 g, 0.82 mol) were dissolved in 900 mL of EtOH and transferred to a 4 L round bottom flask equipped with a mechanical stirrer and brought to reflux. Excess KOH (45.9 g, 0.82 mol) in EtOH was added dropwise into the refluxing mixture. After addition, the mixture was mechanically stirred and refluxed for 3 days. After cooling, 1

(9) Dingle, T. W.; Wan, P. Unpublished work.

(10) Wan, P.; Chak, B.; Krogh, E. *J. Photochem. Photobiol., A* **1989**, *46*, 49.

(11) Bates, R. G. In *Determination of pH-Theory and Practice*; Wiley: New York, 1973.

L of H_2O was added and the resulting solution extracted with diethyl ether and back washed with 0.1 M ice-cold NaOH. The extract was dried over $MgSO_4$ and the solvent evaporated. Subsequent bulb-to-bulb distillation afforded 36 g (47%) of the corresponding diester of resorcinol as a viscous colorless oil: ^1H NMR (90 MHz) δ 1.3 (t, 6H, $J = 6$ Hz), 4.2 (q, 4H, $J = 6$ Hz), 4.6 (s, 4H), 6.5–7.3 (m, 4H). This material was reduced with $LiAlH_4$ as follows. The diester (20 g, 0.07 mol) was dissolved in 250 mL of dry THF and excess $LiAlH_4$ (4.0 g, 0.11 mol) was added in portions after which the reaction mixture was refluxed for 3 h. Standard workup gave 11.4 g (81%) of **3** as a white solid on standing: ^1H NMR (360 MHz) δ 2.04 (t, $J = 6$ Hz, 2H), 3.92–4.06 (m, 8H), 6.49 (t, $J = 2$ Hz, 1H), 6.52 (dd, $J = 8$ and 2 Hz, 2H), 7.17 (t, $J = 8$ Hz, 1H); MS (EI) 198 (M^+).

1,3-Diethoxybenzene-2-d (8). This was prepared by quenching of the 2-lithio derivative of **2** formed by the reaction of **2** with *n*-BuLi using the procedure described recently.[5b] The ^1H NMR of the resulting material was identical to that of **2** except with the absence of the resonance of proton 2 and associated couplings, MS (EI) 167 (M^+).

Product Studies. In general, 2–50 mg samples were dissolved in the appropriate solvent mixture (3–100 mL) and irradiated in 3.0 mL Suprasil quartz cuvettes or 100–200 mL quartz tubes, depending on the scale of the experiment. Except for runs in cuvettes, solutions were cooled by a cold finger and stirred by a stream of argon. Cuvette samples were purged with argon prior to photolysis and were cooled by air. A merry-go-round apparatus was used for these samples. Typical experiments are described below.

Photolysis of 2 in Aqueous D_2SO_4–CH_3CN. Substrate **2** (55 mg) was irradiated in 2:1 10% D_2SO_4–CH_3CN (45 mL) at 254 nm for 30 min. After irradiation, 50 mL of H_2O was added and the solution was extracted with 3 × 100 mL of CH_2Cl_2. After evaporation of the solvent, the crude photolysate was analyzed by ^1H NMR (250 or 360 MHz): δ 1.40 (t, $J = 8$ Hz, 6H, CH_3), 4.00 (q, $J = 8$ Hz, 4H, $ArCH_2O$), 6.45 (t, $J = 2$ Hz, H2, reduced in intensity; 90% deuterium exchanged by integration), 6.51 (d, $J = 8$ Hz, H4, absence of coupling to H2; reduced intensity consistent with deuterium exchange (5–10%) at H4), 7.15 (t, $J = 8$ Hz, 1H, H5), 7,15 (d, $J = 8$ Hz, H5, due to some deuterium exchange at H4). A dark control reaction as above confirmed that exchange at H4 was a thermal process.

Photolysis of 4 in Aqueous D_2SO_4–CH_3CN. Substrate **4** was photolyzed as described above for 30 min and 2 h. After workup, the material was recovered unchanged. GC analysis showed no additional peaks, ruling out formation of any phenols from *ipso* substitution of the methoxy groups.

Photolysis of 5 in Aqueous D_2SO_4–CH_3CN. Substrate **5** was photolyzed for 30 min. GC analysis of the product mixture showed only one peak corresponding to substrate: ^1H NMR (250 MHz) δ 2.17 (s, 3H, CH_3), 3.8 (s, 6H, OCH_3), 6.43 (d, 1H, H6, 10–20% deuterium exchanged by integration), 6.47 (d, 1H, H2, 60% deuterium exchanged), 7.05 (d, 1H, H5, 10% deuterium exchanged). In addition, the new singlets at δ 6.43

and 7.05 confirm deuterium incorporations at both C5 and C6. A dark run showed exchange only at C6.

Photolysis of 6 in Aqueous D_2SO_4–CH_3CN. GC analysis of the photolyzed material (30 min) showed no new peaks. ^1H NMR (250 MHz) analysis showed deuterium incorporation at H2 (δ 6.49, 50% deuterium exchanged) as well as at H5 and H6 (10% each) due to new singlets appearing at these resonances (δ 6.36 (H5) and 6.74 (H6)). A dark reaction showed only deuterium incorporation at H6.

Photolysis of 7 in Aqueous D_2SO_4–CH_3CN. Photolysis of **7** as above for 1–2 h gave no new photoproducts (GC) or deuterium exchange (^1H NMR), and the material was recovered unchanged.

Exchange Quantum Yields. Quantum yields were measured using a Rayonet RPR 100 photochemical reactor (16 × 254 nm lamps). Solutions ($\approx 10^{-3}$ M) were prepared in 3.0 mL quartz cuvettes and purged with a stream of argon prior to photolysis. Potassium ferrioxalate was used for chemical actinometry.[12] After photolysis, the sample was extracted several times with CH_2Cl_2 and conversions were (kept <20%) analyzed by GC/MS using selected ion monitoring on the Kratos Concept H instrument (EI).

Fluorescence Measurements. Fluorescence emission spectra (uncorrected) were taken in 3.0 mL quartz cuvettes at $\approx 10^{-4}$ M using a Perkin-Elmer MPF 66 spectrophotometer at ambient temperature (22 ± 2 °C; $\lambda_{ex} = 265$ nm; slit width 2 nm). Samples for fluorescence measurements were initially deaerated by argon purging prior to measurement. However, this had no measurable effect on fluorescence emission yields or lifetimes. Subsequently, all samples were used without deaeration. Fluorescence quenching experiments were carried out in wholly aqueous media, by injecting a known volume (typically 10–20 μL) of a stock solution of the substrate dissolved in CH_3CN using a microliter syringe into a 3.0 mL solution of the appropriate acidity. For fluorescence quantum yield measurements (in 4:1 H_2O–CH_3CN), optical densities at $\lambda_{ex} = 265$ nm were matched with the external standard prior to measurement. Fluorescence lifetimes (wholly aqueous medium) were measured at room temperature on a standard single photon counting instrument (PTI LS-1 spectrofluorimeter equipped with single photon electronics) using a hydrogen spark lamp as excitation source. Decays were analyzed using software supplied by PTI.

(12) (a) Hatchard, C. G.; Parker, C. A. *Proc. R. Soc. (London)* **1958**, *A235*, 518. (b) Murov, S. L. *Handbook of Photochemistry*; M. Dekker: New York, 1973.