# Photocyclization of 2-(2'-Hydroxyphenyl)benzyl Alcohol and Derivatives via *o*-Quinonemethide Type Intermediates[1]

**C.-G. Huang, Kathryn Anne Beveridge, and Peter Wan***

*Contribution from the Department of Chemistry, P.O. Box 3055, University of Victoria, Victoria, British Columbia, Canada V8W 3P6.* *Received October 5, 1990. Revised Manuscript Received May 11, 1991*

**Abstract:** A new photochemical reaction, the photocyclization of 2-(2'-hydroxyphenyl)benzyl alcohol (**1**) and derivatives to 6*H*-dibenzo[*b*,*d*]pyrans, is reported. The quantum yield for cyclization of **1** to give pyran **7** is 0.50 ± 0.04 in aqueous solutions of pH > 10. At lower pH, Φ is significantly lower. For example at pH 7, Φ = 0.25 ± 0.03. Results from investigations of structure–reactivity, pH effects, and fluorescence data suggest a mechanism in which the primary step involves ionization of the phenol moiety to phenolate in $S_1$, which is probably followed by (or is concerted with) twisting of the phenyl rings to give a more planar species in the excited state. This is subsequently followed by (or is concerted with) a dehydroxylation step of the benzyl alcohol moiety (all on the $S_1$ surface) to give an *o*-quinonemethide type intermediate **20** and deactivation back to the ground-state surface. Electrocyclic ring closure of this intermediate gives the observed pyran. Nucleophilic trapping of this electrophilic intermediate by solvent (e.g., MeOH) to give the methyl ether is also observed when photolysis is carried out in MeOH. The proposed reaction pathway is unprecedented: it takes advantage of the tendency of biphenyl systems to be planar in the excited state as well as the enhanced electron-donating effect of the phenolate anion, which is required for the dehydroxylation step.

## Introduction

In general, biphenyl derivatives have twisted ground-state structures[2] in the solid state, with dihedral (also known as interplanar or torsional) angles in the range 10–40° for most derivatives.[3] Dihedral angles for *o*,*o*'- and *o*,*o*-disubstituted biphenyls are significantly larger and are in the 50–80° range.[2] There is much evidence to indicate that in the excited state, biphenyl systems have an inherent twisting motion towards planarity to gain a better overlap of the π-systems of the two benzene rings.[6] The photoisomerization of several optically active biphenyl derivatives utilizes this phenomenon to drive this reaction, which would otherwise be difficult to accomplish in the ground state.[6c,d] However, apart from several electrocyclic ring-closure reactions reported for some biphenyl derivatives,[7] little additional work has been reported to take full advantage of the inherent twisting motion toward planarity to accomplish new photochemistry of biphenyl derivatives. We report here the results of a study of a new photochemical reaction of appropriately substituted biphenyls, which makes use of the tendency toward planarity in the excited state, coupled with charge transfer from an electron-rich phenolate ion to accomplish a cyclization that would otherwise require much harsher conditions to be accomplished in the ground state.

**Table I.** Summary of Crystallographic Data for **1** and **6**

| | **1** | **6** |
|---|---|---|
| formula | $C_{13}H_{12}O_2$ | $C_{15}H_{16}O_2$ |
| MW | 200.2 | 228.3 |
| crystal system | monoclinic | monoclinic |
| space group | *Cc* | $P2_1c$ |
| cell dimensions | | |
| *a*, Å | 13.180 (5) | 11.973 (1) |
| *b*, Å | 6.448 (2) | 7.376 (2) |
| *c*, Å | 12.096 (4) | 7.161 (1) |
| α, deg | 90 | 90 |
| β, deg | 96.80 (4) | 104.13 (1) |
| γ, deg | 90 | 90 |
| *V*, Å$^3$ | 1020.7 | 613.27 |
| *Z* | 4 | 2 |
| *T* | 20 °C | 20 °C |
| λ | Mo Kα (0.71069) | Mo Kα (0.71069) |
| $\rho_{obsd}$, g cm$^{-1}$ | 1.297 | 1.2296 |
| $\rho_{calcd}$, g cm$^{-1}$ | 1.303 | 1.236 |
| μ, cm$^{-1}$ | 0.93 | 0.45 |
| $R(F_o)$ | 0.095 | 0.0412 |
| $R_w(F_o)$ | 0.105 | 0.0429 |

## Results and Discussion

**Materials.** The biphenyl derivatives of interest (**1**–**6** and **19**) were made via known procedures except for **2** and **3**, which were purchased from Aldrich. The ground-state crystal structures of **1** (2-(2'-hydroxyphenyl)benzyl alcohol) and **6** (2-(2'-hydroxyphenyl)-α,α-dimethylbenzyl alcohol) were determined by X-ray crystallography from single crystals grown from toluene/MeOH. This was carried out to determine the extent of twisting between the benzene rings of these compounds and the arrangement of the *o*,*o*'-substituents in the crystalline state. Crystallographic data are summarized in Table I. ORTEP views of **1** and **6** are shown in Figure 1. The dihedral angle between the benzene rings was 68° for **1** and 72° for **6**. Furthermore, it is clear that in the solid state of these two compounds, the preferred conformation has the substituents on the two rings syn to one another (when viewed along the molecular axis and considering only the non-hydrogen substituents). This is generally observed for *o*,*o*'-disubstituted biphenyls although the reasons for this remain unknown.[2c,8]

(1) Presented in part at the 13th IUPAC Symposium on Photochemistry, University of Warwick, Coventry, England, July 22–28, 1990, and at the 3rd Winter Conference of the Interamerican Photochemical Society, Clearwater Beach, FA, January 1–5, 1991.

(2) (a) Brock, C. P.; Minton, R. P. *J. Am. Chem. Soc.* **1989**, *111*, 4586. (b) Ried, W.; Freitag, D. *Angew. Chem., Int. Ed. Engl.* **1968**, *7*, 835. (c) Roberts, R. M. G. *Magn. Reson. Chem.* **1985**, *23*, 52.

(3) The parent biphenyl molecule is anomalous in this regard because it is known to be flat in the solid state at room temperature[4] but is ca. 15–30° twisted in solution.[5]

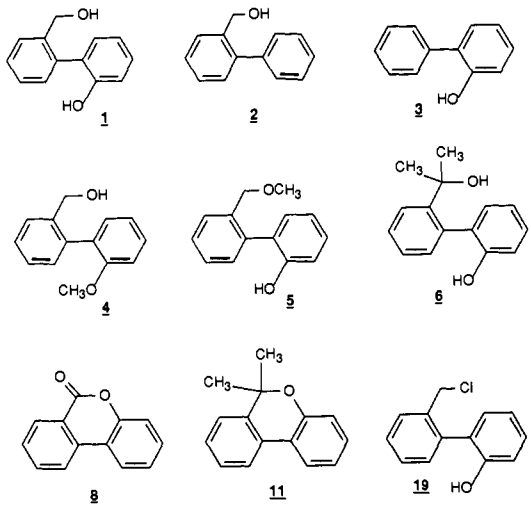
(4) (a) Hochstrasser, R. M.; Sung, H. N. *J. Chem. Phys.* **1977**, *66*, 3265. (b) Hargreaves, A.; Rizvi, S. H. *Acta Crystallogr.* **1962**, *15*, 365.

(5) (a) Suzuki, K. *Bull. Chem. Soc. Jpn.* **1959**, *32*, 1340. (b) Kurland, R. J.; Wise, W. B. *J. Am. Chem. Soc.* **1964**, *86*, 1877. (c) Eaton, V. J.; Steele, D. *J. Chem. Soc., Faraday Trans. 2* **1973**, *69*, 1601. (d) Lim, E. C.; Li, Y. H. *J. Chem. Phys.* **1970**, *52*, 6416. (e) Uchimura, H.; Tajiri, A.; Hatano, M. *Chem. Phys. Lett.* **1975**, *34*, 34. (f) Uchimura, H.; Tajiri, A.; Hatano, M. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 3279.

(6) (a) Werner, T. C. In *Modern Fluorescence Spectroscopy*; Wehry, E. L., Ed.; Plenum Press: New York, 1976; Vol. 2. (b) Takei, Y.; Yamaguchi, T.; Osamura, Y.; Fuke, K.; Kaya, K. *J. Chem. Phys.* **1988**, *92*, 577. (c) Zimmerman, H. E.; Crumrine, D. S. *J. Am. Chem. Soc.* **1972**, *94*, 498. (d) Mislow, K.; Gordon, A. J. *J. Am. Chem. Soc.* **1963**, *85*, 3521. (e) Wagner, P. J. *J. Am. Chem. Soc.* **1967**, *89*, 2820. (f) Hoffmann, R.; Imamura, A. *J. Am. Chem. Soc.* **1968**, *90*, 5379.

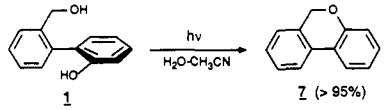
(7) (a) Padwa, A.; Doubleday, C.; Mazzu, A. *J. Org. Chem. Soc.* **1977**, *42*, 3271. (b) Lazare, S.; Lapouyade, R.; Bonneau, R. *J. Am. Chem. Soc.* **1985**, *63*, 2192. (c) Lapouyade, R.; Manigand, C.; Nourmamoude, A. *Can. J. Chem.* **1985**, *63*, 2192. (d) Taylor, E. C.; Furth, B.; Pfau, M. *J. Am. Chem. Soc.* **1965**, *87*, 1400. (e) Swenton, J. S.; Ikeler, T. J.; Smyser, G. L. *J. Org. Chem.* **1973**, *38*, 1157 and references cited therein.

0002-7863/91/1513-7676$02.50/0 



Although the X-ray structures of **1** and **6** clearly show a highly twisted geometry, one could not infer a solution structure simply on the basis of X-ray data. However, Roberts[2c] has shown by use of a $^{13}C$ NMR spectroscopy technique that the dihedral angles of several biphenyl derivatives, including some *o,o'*-disubstituted systems, have solution dihedral angles that agree well with those measured in the solid state. It is reasonable to assume that both **1** and **6** would also have large dihedral angles in solution. Simple calculations using molecular mechanics programs (PCMODEL or ALCHEMY II) also indicate a preference for a highly twisted geometry about the biphenyl bond. However, it is not possible to determine whether the solution structure has the ortho substituents syn or anti, although the X-ray structures clearly show a preference for the syn geometry in the solid state.

**Product Studies.** Photolysis of $10^{-4}$–$10^{-2}$ M aqueous $CH_3CN$ solutions (typically 1:1 or 7:3 $H_2O$–$CH_3CN$) of **1** (Rayonet RPR 100 photochemical reactor, 254-nm lamps, 0.2–2 h, solution was cooled and argon purged) gave >95% yield of 6*H*-dibenzo[*b*,*d*]pyran (**7**) as the only product by GC and $^1H$ NMR analysis (eq 1). The structure of **7** was confirmed by comparison with



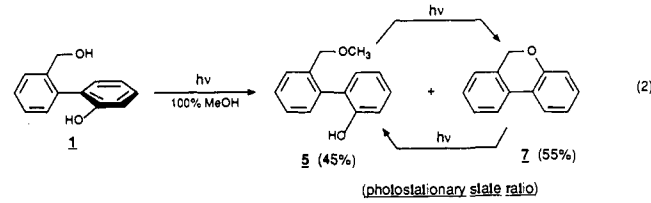
(1)

an authentic sample made by reduction of 2′-hydroxybiphenyl-2-carboxylic acid lactone (**8**) according to the procedure by Devlin.[9a] Without irradiation, alcohol **1** was stable indefinitely under the above experimental conditions. Molecular models and molecular mechanics calculations show that pyran **7** is essentially a planar molecule, with a slight puckering out of planarity at the oxygen atom. From ALCHEMY II calculations, the dihedral angle between the two benzene rings of **7** is 10°. Thus the overall transformation (eq 1) takes highly twisted **1** to essentially planar **7** (with formal loss of $H_2O$ from **1**) on photolysis. In the ground state, **1** is stable under a variety of conditions including reflux in acidic aqueous solution. Devlin[9a] has cyclized the *p*-hydroxy derivative of **1** (neat) to the corresponding pyran at 250 °C in 49% yield. The reluctance of **1** to cyclize to **7** in the ground state can at least be partially attributed to its highly twisted structure, which presents a barrier for dehydration/cyclization.

The photocyclization of **1** can be conveniently followed by UV spectroscopy. As shown in Figure 2, photolysis of a deaerated ca. $10^{-4}$ M sample of **1** in aqueous $CH_3CN$ (1:1 $H_2O$–$CH_3CN$ or 100% $H_2O$) resulted in growth of absorption bands at 305 and 265 nm, which can be assigned to pyran **7**. After exhaustive photolysis, the spectrum observed is essentially identical with that of authentic **7** (see inset of Figure 2).

Based on the above data, it would appear that **1** can be converted essentially quantitatively to **7** on irradiation in aqueous $CH_3CN$. To examine this possibility in more detail, the reaction (in 1:1 $H_2O$–$CH_3CN$) was followed by GC as a function of irradiation time (Figure 3). On exhaustive photolysis, the photostationary state was found to be 98:2 for **7**:**1**. This was confirmed by photolysis of authentic **7**, which gave ca. 1–2% yield (by GC analysis) of **1** after exhaustive photolysis. Thus the photoconversion of **1** to **7** is photoreversible to some extent.

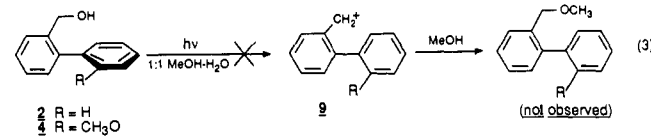
Exhaustive photolysis of **1** in 100% MeOH gave **5** and **7** in a photostationary-state ratio of 45:55 (eq 2). At low conversions (<30%), the ratio of **5**:**7** observed was ca. 2:1; that is, there is a preference for MeOH attack (resulting in overall photosubstitution at the benzylic position) vs cyclization when **1** is photolyzed in 100% MeOH. When an authentic sample of **7** was irradiated



(2)

in 100% MeOH (Figure 4), the only product was **5**, and a photostationary state of 45:55 (for **5**:**7**) was also observed after exhaustive photolysis. These results can only be explained if **5** can also photocyclize to **7**. This was indeed shown to be the case as photolysis of **5** in 100% MeOH gave **7** as the only product. It is clear from these experiments that methanol trapping of the reactive intermediate competes with its cyclization pathway. Furthermore, the results also suggest that photolysis of pyran **7** leads to the *same* reactive intermediate as does photolysis of **1**. Note also that use of MeOH in the photolysis of **7** results in a higher yield of the ring-opened product (**5**) compared to photolysis of **7** in $H_2O$–$CH_3CN$, which gave only 1–2% yield of **1**.

Further insights into the mechanism of photocyclization were obtained by studying biphenyl derivatives **2**–**4** and **6**. Under the above conditions where both **1** and **5** photocyclized to **7** in high yields, none of the compounds **2**–**4** displayed observable photochemistry. On prolonged photolysis, **2** photoisomerized to *m*-phenylbenzyl alcohol.[9b] In addition, extended photolysis of **2** and **4** in 1:1 $H_2O$–MeOH (pH of the $H_2O$ portion was varied from 1 to 13) or 100% MeOH gave no observable photosolvolysis reaction (eq 3). This latter observation argues against a reaction



(3)

mechanism involving initial photodehydroxylation of the benzyl alcohol moiety in **1** (or the corresponding demethoxylation for **5**) to generate a carbocation intermediate **10**, followed by intramolecular attack (with twisting) by the phenol moiety (in a ground-state step) to give **7** (eq 4). If this mechanism was operative, one or both of **2** and **4** would have photosolvolyzed in aqueous MeOH to give the corresponding methyl ether.[10] It is

(8) One could argue that at least for **1** and **6**, the preference for syn geometry of the *o,o'*-substituents in the crystal is due to a preference for intramolecular hydrogen bonding between the substituents. However, syn geometry is also observed for derivatives that cannot form intramolecular hydrogen bonding.[2c]

(9) (a) Devlin, J. P. *Can. J. Chem.* **1975**, *53*, 343. (b) The mechanism of this isomerization probably involves benzvalene intermediates and resembles the photoisomerization of 2-phenyltoluenes: (i) Abramovitch, R. A.; Takaya, T. *J. Chem. Soc., Chem. Commun.* **1969**, 1369. (ii) Mende, U.; Laseter, J. L.; Griffin, G. W. *Tetrahedron Lett.* **1970**, 3747.

(10) We have shown[11a] that photosolvolysis of simple benzyl alcohols is an efficient reaction in *neutral* solution only if methoxy substituents are present at the meta or ortho positions. An *o*-phenyl group is not known to activate benzyl alcohol sufficiently to result in photosolvolysis. The high photosolvolytic reactivity observed for 9-fluorenol (which may be regarded as a benzyl alcohol derivative) and derivatives has been interpreted as being due to the favorability for attaining a 4$\pi$ cyclic array in the fluorenyl cation intermediate on the excited state surface.[11b] It is clear that none of the compounds **1**–**6** and **19** contain this structural feature.

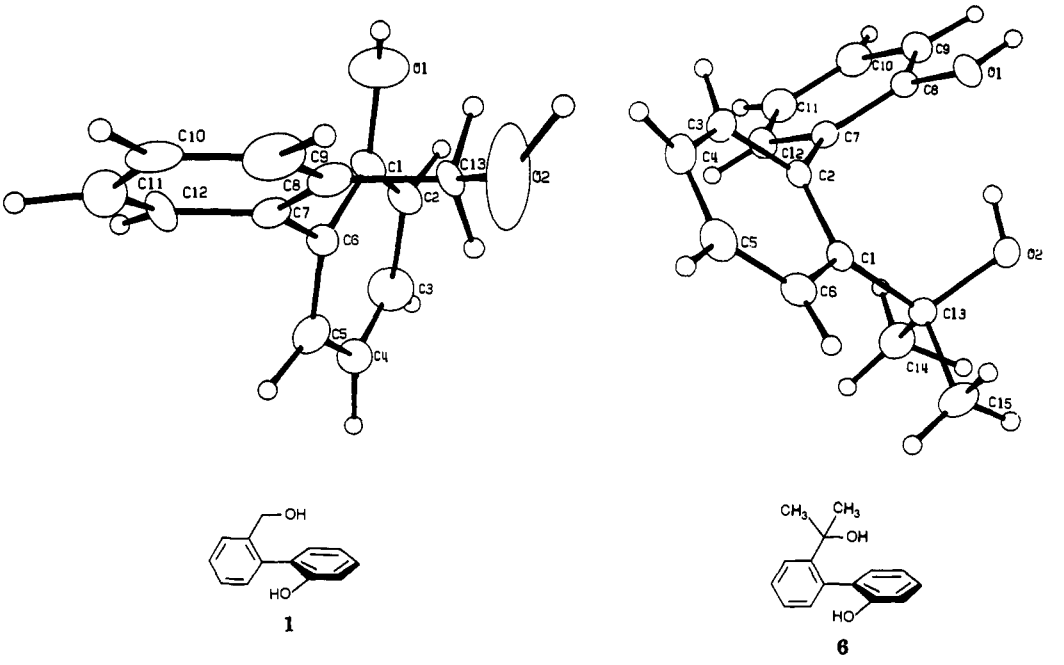



**Figure 1.** ORTEP drawings of biphenyl alcohols **1** and **6**. Note that both structures have the ortho substituents in the syn geometry in the solid state. The dihedral angles (between the two benzene rings) are 68° and 72° for **1** and **6**, respectively.

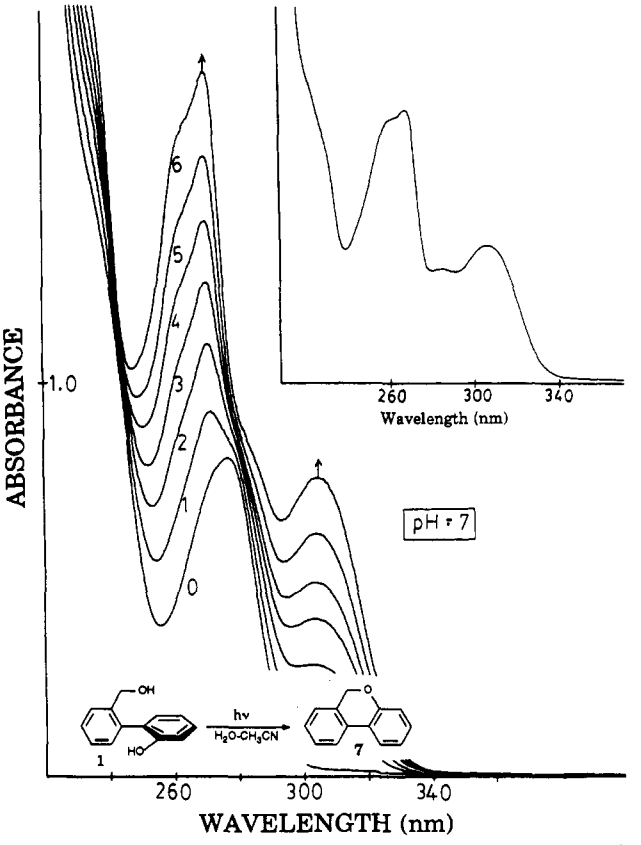



**Figure 2.** UV absorption traces in the photolysis of **1** in 1:1 $H_2O$–$CH_3CN$. Each trace represents ca. 15 s photolysis at 254 nm inside a Rayonet reactor employing a merry-go-round assembly. The inset is a spectrum of authentic **7** in the same solvent, which matches one obtained from an exhaustively irradiated sample of **1**.

clear that a *phenol* moiety on the adjacent ring is a *necessary* requirement for photocyclization of these biphenyl alcohols. However, the observation of a MeOH-trapping product competing the photocyclization on photolysis of **1** (eq 2) indicates that the

(11) (a) Wan, P.; Chak, B. *J. Chem. Soc., Perkin Trans. 2* **1986**, 1751. (b) Wan, P.; Krogh, E. *J. Am. Chem. Soc.* **1989**, *111*, 4887.

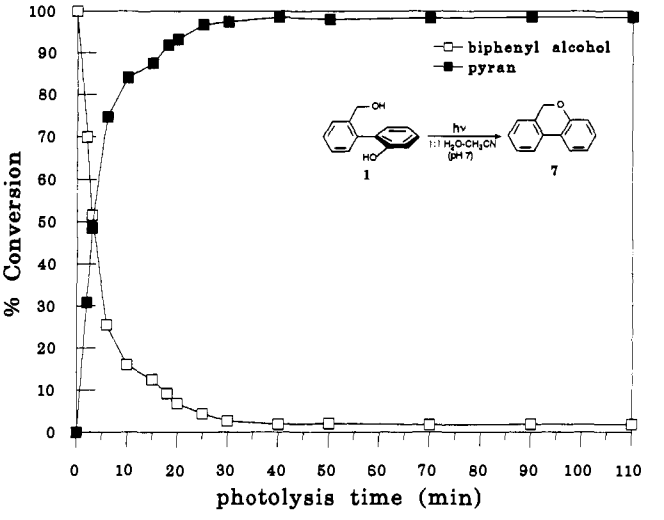



**Figure 3.** Yield of pyran **7** as a function of irradiation time on photolysis of **1** in 1:1 $H_2O$–$CH_3CN$.

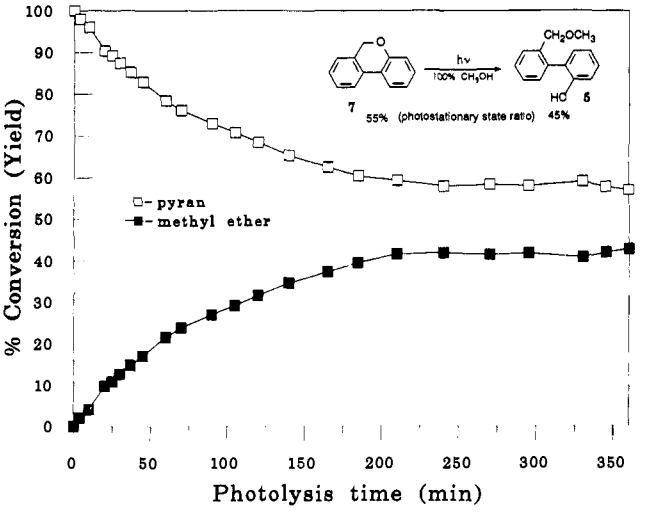



**Figure 4.** Yield of methyl ether **5** as a function of irradiation time on photolysis of **7** in 100% MeOH.

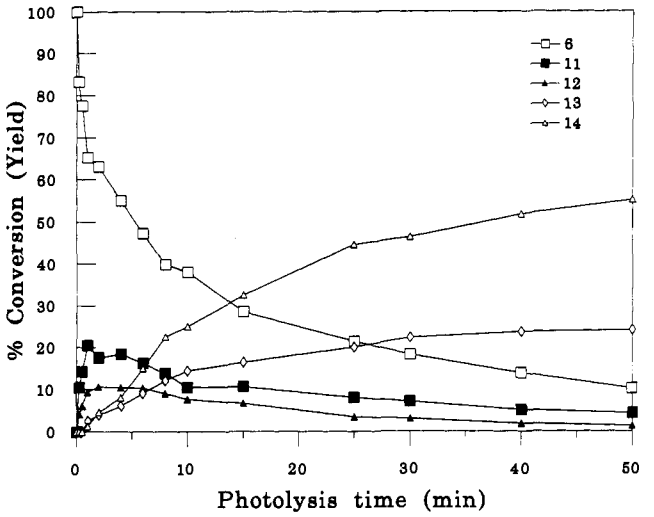
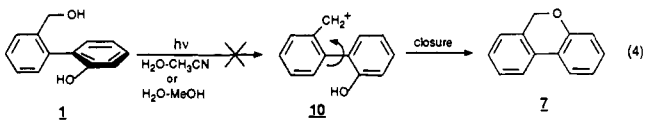
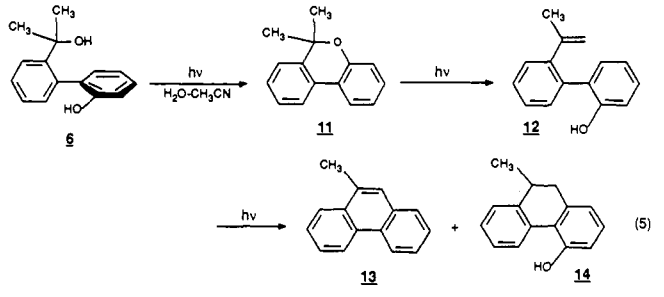



**Figure 5.** Kinetic plot of product yields vs irradiation time in the photolysis of alcohol **6** in 1:1 $H_2O$–$CH_3CN$.

reaction of **1** proceeds via an intermediate that must have electrophilic character at the benzylic carbon end. The above results show that (i) this intermediate is *not* the simple carbocation **10** shown in eq 4, and (ii) this same intermediate can be generated on photolysis of **7**.

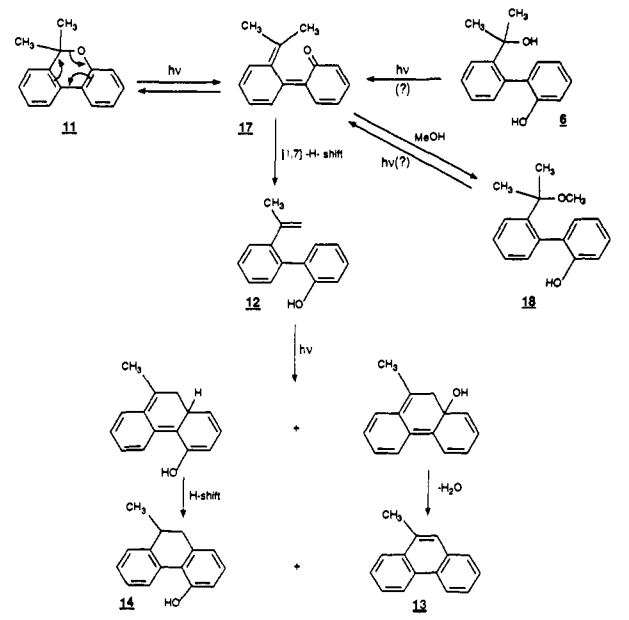



Product studies of biphenyl alcohol **6** provided additional information on the mechanism of photocyclization. Photolysis of **6** in 1:1 $H_2O$–$CH_3CN$ gave a mixture of products shown in eq 5. The relative yields of these products were found to be very dependent on photolysis time. A subsequent kinetic study (by GC) (Figure 5) showed that the primary product was pyran **9**, which on secondary photolysis decomposed to styryl derivative **12**. Product **12** was also photolabile and reacted to give **13** (ca. 24%) and **14** (ca. 55%) as final products after exhaustive photolysis (Figure 5). The photolability of pyran **11**[12a] and a derivative[12b] has been reported by Turnbull and co-workers. They found that photolysis of **11** (in EtOH) gave initially **12**, followed by **13** and **14** as final products. Their results corroborate the proposed pathway for the overall photochemistry observed for **6** shown in eq 5.

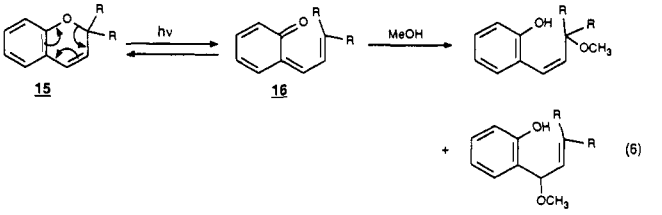



Electrocyclic ring opening of the pyran ring in chromene systems **15** to give *o*-quinonemethide type intermediates **16** is a well-known reaction (eq 6). For example, Padwa and co-workers[13] have shown in a series of papers that intermediates of the type **16** can either

Scheme I




return to **15** or be trapped by nucleophilic solvents, such as MeOH, to give methyl ether addition products (eq 6). That *o*-




quinonemethides are electrophilic species at the benzylic carbon has also been amply demonstrated for a variety of these reactive intermediates.[14] In addition, Lenoble and Becker[15] have characterized *o*-quinonemethides **16** via transient absorption by using laser flash photolysis. In EtOH solution, **16** (R = Ph) ($\lambda_{max}$ = 410 and 500 nm) had a lifetime in the microsecond range and a rise time of <1 ns. The ring opening was shown to be via the $S_1$ state of **15** (R = Ph).

With the above as background, a reasonable mechanism for the photochemistry of pyran **11** is shown in Scheme I. The first step is electrocyclic ring opening of the pyran ring to give the *o*-quinonemethide type intermediate **17**. On the basis of literature precedent (vide supra), this *o*-quinonemethide type intermediate **17** should be trappable by nucleophilic solvents. We have confirmed this by photolyzing **11** in 100% MeOH, which gave low yields (<10%) of methyl ether **18**. The low yields can be accounted for since there is a competing *irreversible* pathway that efficiently removes all of **6**, **11**, and **18** to **12** (Scheme I). The transformation of **17** to **12** (and then to final products **13** and **14**) probably occurs via a 1,7-hydrogen shift from the methyl group of **17** to the carbonyl oxygen on the adjacent ring in a thermal reaction. Several groups[7a,b,c] have shown that 2-vinylbiphenyl derivatives undergo efficient electrocyclic ring closure on photolysis to give phenanthrene derivatives as final products. The same reaction of **12** would be expected to give both **13** and **14**, which are in fact the final products. The possibility that both **6** and **18** give rise to **17** on photolysis will be addressed below and in the overall discussion of the mechanism to follow later.

Additional insight into the pathway in which **6** is transformed to **11** on photolysis comes from an examination of the kinetic plot shown in Figure 5. The plot shows that the growth of products

(12) (a) Bowd, A.; Turnbull, J. H.; Coyle, J. D. *J. Chem. Res. Synop.* **1980**, 202. (b) Bowd, A.; Swann, D. A.; Turnbull, J. H. *J. Chem. Soc., Chem. Commun.* **1975**, 797.

(13) (a) Padwa, A.; Lee, G. A. *J. Chem. Soc., Chem. Commun.* **1972**, 795. (b) Padwa, A.; Owens, W. *J. Chem. Soc., Chem. Commun.* **1974**, 675. (c) Padwa, A.; Au, A.; Lee, G. A.; Owens, W. *J. Org. Chem.* **1975**, *40*, 1142. (d) Padwa, A.; Au, A.; Lee, G. A.; Owens, W. *J. Am. Chem. Soc.* **1976**, *98*, 3555.

(14) Karabelas, K.; Moore, H. W. *J. Am. Chem. Soc.* **1990**, *112*, 5372 and references quoted therein.

(15) Lenoble, C.; Becker, R. S. *J. Photochem.* **1986**, *33*, 187 and references quoted therein.

Table II. Quantum Yields for Photocyclization of Biphenyl Derivatives 1, 5, 6, and 19

| substrate | condition[a] | $\Phi$[b] |
|---|---|---|
| 1 | 100% $CH_3CN$ | 0.12 ± 0.01 |
| | 1:1 $H_2O$–$CH_3CN$ | 0.21 ± 0.02 |
| | 7:3 $H_2O$–$CH_3CN$ | 0.25 ± 0.03 |
| 5 | 100% $CH_3CN$ | 0.080 ± 0.003 |
| | 1:1 $H_2O$–$CH_3CN$[c] | 0.13 ± 0.02[c] |
| 6 | 1:1 $H_2O$–$CH_3CN$[d] | 0.20 ± 0.03[d] |
| 19 | 100% $CH_3CN$ | 0.050 ± 0.003 |
| | 1:1 $H_2O$–$CH_3CN$[c] | 0.11 ± 0.02[c] |

[a] The $H_2O$ portion of these solutions was buffered at pH 7. [b] Quantum yield for formation of pyran 7 unless otherwise noted. [c] Predominant product was pyran 7 (95%) with a trace of 1 (5%) in this solvent. [d] Quantum yield for loss of 6 (pyran 11 is the initially formed product, which was found to be photolabile, see text).

11 and 12 (at early photolysis times) is almost equally fast. If 11 is indeed the first-formed product, which subsequently photodecomposes to 12 (eq 5), one would have expected a more significant delay before product 12 is observed. The rapid rise of 12 is consistent with a modified reaction scheme in which photolysis of 6 gives *o*-quinonemethide intermediate 17, which can either cyclize to 11 or undergo a 1,7-hydrogen shift to give 12 as a *competing* reaction (Scheme I). The proposal of a common intermediate on photolysis of 11 or 6 was already suggested by product studies of 1, 5, and 7 in MeOH (vide supra).

**$^{18}O$ Incorporation from Photolysis in $H_2{}^{18}O$.** The results presented so far suggest that the oxygen in the pyran product (7 or 11) comes from the phenol moiety. For example, photolysis of 5 gave 7 (eq 2). The MeOH that must be lost in this reaction most likely came from the benzylic $OCH_3$ group. Additional support for this pathway is that photolysis of chloride 19 also gave 7 in high yields. The final possibility that has to be eliminated is that the pyran oxygen comes from solvent $H_2O$ (or solvent $CH_3OH$ when it is used). We have found that photolysis of 1 in 20% $H_2{}^{18}O$-enriched 1:1 $H_2O$–$CH_3CN$ (taken to 50% conversion to 7) resulted in no observable incorporation of $^{18}O$ into pyran 7 (by GC/MS analysis). In principle, this experiment also allowed us to monitor $^{18}O$ incorporation into recovered 1. However, 1 efficiently loses $H_2O$ in the mass spectrometer (presumably cyclizing to 7) so that it was not possible to monitor the molecular ion (CI or EI modes). The observation of a MeOH-trapping product (5) on photolysis of 1 (eq 2) would argue that there is also significant trapping of the reactive intermediate by water to give back 1, competing with its cyclization to 7.

**Quantum Yield Measurements.** Quantum yields ($\Phi$) for formation of 7 from photolysis of 1, 5, and 19 were measured in aqueous $CH_3CN$ and are given in Table II. Due to the formation of several products on photolysis of 6, only the quantum yield for loss of 6 was estimated.

Quantum yields ($\Phi$) for formation of 7 from 1 have also been measured in 7:3 $H_2O$–$CH_3CN$ where the pH ($H_0$) of the aqueous portion was varied over the whole pH range and into moderately concentrated $H_2SO_4$ solution. Dark control runs showed that no cyclization was observed without irradiation. $\Phi$ was found to vary significantly with pH ($H_0$) (Figure 6). There are two inflection points in the plot, one at pH ≈ 10 and the other at pH ≈ 1, and a plateau region between 2 and 9. Above pH 10, 1 exists in the phenolate ion form in the ground state.[16] Excitation of the phenolate ion of 1 resulted in the highest quantum yield for cyclization ($\Phi$ = 0.50 ± 0.04). The second inflection point at pH ≈ 1 is associated with the excited state $pK_a$ of the phenol. Because the fluorescence emission from 1 was very weak at all pHs (vide infra), it was not possible to carry out accurate fluorescence titration of the phenol moiety of 1 and estimate its $pK_a(S_1)$. However, the structurally related phenol 3 (which was unreactive) was found to be very emissive. Fluorescence titration (vide infra) gave $pK(S_1)$ = 1.5 ± 0.3 for the phenol moiety of 3. The expected

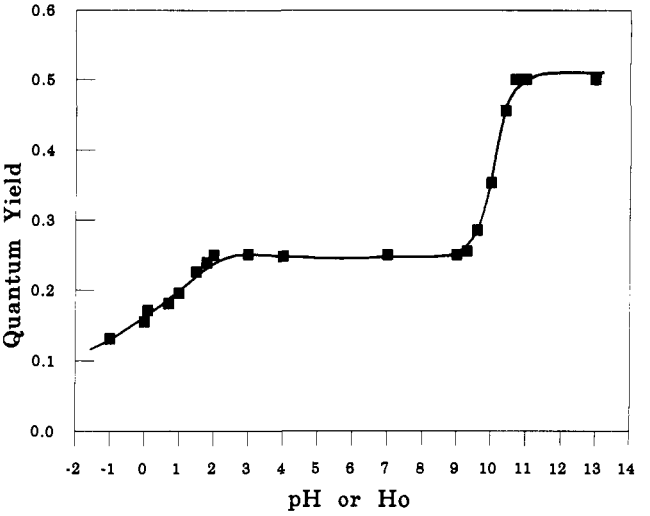



Figure 6. Plot of quantum yield ($\Phi$) for formation of 7 on photolysis of 1 as a function of pH in 7:3 $H_2O$–$CH_3CN$ (quoted pH is of the aqueous portion only).

Table III. Quantum Yields for Photocyclization of 1 to 7 at Different Light Intensities[a]

| light intensity[b] | $\Phi$[c] |
|---|---|
| $0.80 \times 10^{-7}$ | 0.19 ± 0.03 |
| $2.3 \times 10^{-7}$ | 0.20 ± 0.03 |
| $2.9 \times 10^{-7}$ | 0.25 ± 0.03 |

[a] Quantum yields in 7:3 $H_2O$–$CH_3CN$ (water portion at pH 7). [b] In einsteins $min^{-1}$. Exciting wavelength = 280 nm; light intensity was varied by changing the slit width of the exit monochromator. Intensity monitored by potassium ferrioxalate actinometry. Estimated error ±5% of quoted value. [c] Measured by GC.

$pK_a(S_1)$ of 1 should be close to this value. Phenols of comparable and stronger acidity in $S_1$ have recently been reported by Tolbert and Haubrich.[17] For example, several appropriately substituted naphthols have $pK_a(S_1)$ values approaching 0. The presently determined $pK_a(S_1)$ of ca. 1.5 for biphenyl phenol 3 does not seem unreasonable in light of these values. Thus, the observation that $\Phi$ for photocyclization of 1 *increases* from moderately strong acid ($H_0 < 0$) to ca. pH 3 and then reaches a plateau region (until pH 10) indicates that the photocyclization *also arises from the excited-state phenolate ion* at these acidities because the inflection point occurs at essentially the expected $pK_a(S_1)$ for 1. Therefore, the mechanism of photocyclization in this pH region (ca. −1 to 10) must involve deprotonation of the initially excited protonated phenol 1 on the excited-state surface.

Figure 6 also shows that $\Phi$ does not go to zero in more strongly acidic media as might be expected, since all excited states in this acidity region would remain protonated. There appears to be an additional photocyclization pathway at these higher acidities that

(16) The ground state $pK_a$ of 1 and 3 were determined by spectrophotometric titration and found to be 9.9 ± 0.3 and 10.2 ± 0.3, respectively (100% $H_2O$).

(17) Tolbert, L. M.; Haubrich, J. E. *J. Am. Chem. Soc.* **1990**, *112*, 8163 and references quoted therein.

(18) The triplet energy of 1 was taken to be close to that of biphenyl ($E_T$ = 66 kcal $mol^{-1}$)[19a,b] or 4-hydroxybiphenyl ($E_T$ = 64 kcal $mol^{-1}$).[19a] Benzophenone and acetophenone derivatives have $E_T$ in the range 68–70 and 71–73 kcal $mol^{-1}$,[19] respectively, and therefore, the water-soluble derivatives chosen should be able to transfer triplet energy efficiently. Unfortunately, the availability of water-soluble triplet sensitizers with $E_T$ > 73 kcal $mol^{-1}$ *with* significant absorption >300 nm is limited. This prevented us from using higher energy triplet sensitizers, which would have been desirable. From fluorescence data, however, it is clear that the singlet state is involved in the cyclization. Because we were not able to use a variety of triplet sensitizers of higher $E_T$, the possibility of a minor contribution to the reaction via the triplet state cannot be completely ruled out at this time. Since the triplet states of phenols do not have $pK_a$'s that are significantly different from the ground-state values,[20] the inflection point observed at pH ≈ 1 (Figure 6) can only be attributed to the $S_1$ state and hence its involvement in the mechanism.

(19) (a) Murov, S. L. *Handbook of Photochemistry*; M. Dekker: New York, 1973. (b) Scaiano, J. C., Ed. *Handbook of Organic Photochemistry*; CRC Press: Boca Raton, 1989; Vol. 1.

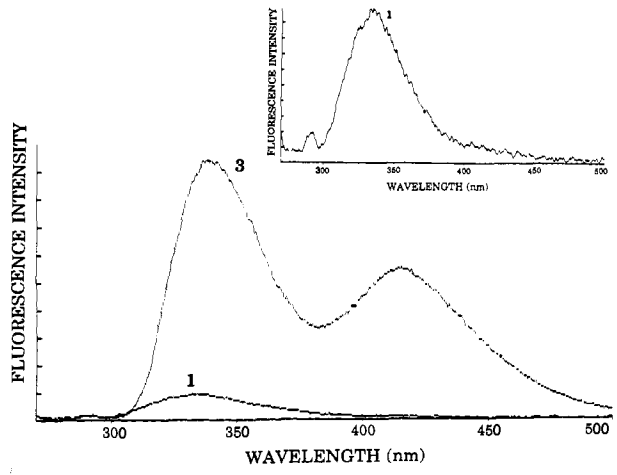



**Figure 7.** Fluorescence spectra of **1** and **3** in 1:1 $H_2O$–$CH_3CN$ ($\lambda_{excit}$ = 265 nm, optical densities at this wavelength were matched for the two substrates). Inset: emission of **1** using expanded sensitivity scale.

will be discussed in a later section.

The possibility that a mechanism requiring two or more photons to convert **1** to **7** needs to be addressed. Although such a possibility is unlikely with the kind of irradiation apparatus used in these studies, there might be a situation where an intermediate was photogenerated that had a significant lifetime, which goes to product only on absorption of an additional photon, but which would otherwise return to substrate. We emphasize that no transient intermediates (limit of detection, $\tau_{1/2} \geq 3$ min) have been observed by UV–vis spectrophotometry or NMR in these reactions. However, in order to rule out the above possibility in a more rigorous manner, we have measured quantum yields of photocyclization of **1** at several different light intensities ($\lambda_{excit}$ = 280 nm) (Table III). We observed no significant dependence on $\Phi$ on light intensity over a 4-fold change in light intensity. It is clear from these results that a mechanism involving two or more photons in the photocyclization mechanism of **1** to **7** is unlikely.

**Steady-State and Transient Fluorescence Measurements.** Fluorescence emission spectra (uncorrected) of **1** and **3** were taken in 1:1 $H_2O$–$CH_3CN$ (water portion at pH 7, buffered solution) with $\lambda_{excit}$ = 265 nm and all samples made up with the same optical density (typically <0.1) at this exciting wavelength. The spectra are given in Figure 7 and show that **3** is more fluorescent than **1**. There are two emission bands of comparable intensity observed for **3** ($\lambda_{max}$ = 345 and 425 nm). The long-wavelength band is from the phenolate ion generated from the phenol via excited-state deprotonation ($\Phi_f \approx 0.14$, relative to naphthalene as fluorescence standard, biexponential decay, $\tau_1$ = 4.2 ns (82%) and $\tau_2$ = 1.2 ns (18%)). The short-wavelength band is from the phenol ($\Phi_f \approx 0.25$, $\tau$ = 1.2 ns). These observations show that there is adiabatic deprotonation from the phenol, which is a well-known phenomenon.[20] Fluorescence titration (in 7:3 $H_2O$–$CH_3CN$) gave $pK_a(S_1)$ = 1.5 ± 0.3 for **3**.

When the emission spectrum of **1** was expanded in sensitivity scale (Figure 7, inset), no band assignable to the phenolate was observed. In addition, because of the weakness of the emission, only an estimate of $\Phi_f$ was obtained ($\approx 0.02$), but $\tau$ could not be measured (<0.5 ns) with the single-photon counting system available. The lack of phenolate emission in **1** at pH 7 is consistent with the fact that the phenolate is the reactive form in the photocyclization. That is, all phenolate forms generated at this pH appear to be removed efficiently, unlike the situation for **3** where the compound is photochemically unreactive.

**Triplet-State Sensitization.** To examine the possibility of triplet reactivity directly, triplet sensitization of **1** ($E_T \approx 65$ kcal mol$^{-1}$)[18] with sodium benzophenone-2-carboxylate ($E_T \approx 69$ kcal mol$^{-1}$, $\lambda_{excit}$ = 350 nm)[18] and sodium *p*-acetylbenzenesulfonate ($E_T \approx 71$ kcal mol$^{-1}$, $\lambda_{excit}$ = 350 nm)[18] was carried out. These photolyses failed to give any photocyclization and the substrate was recovered unchanged. Combined with the fluorescence data, it is clear that photocyclization of **1**, **5**, and **19** occurs via $S_1$.

**Photocyclization Mechanism.** The necessary requirement of a phenol moiety for photocyclization *and* photosolvolysis (i.e., photosubstitution observed at the benzylic carbon in competition with photocyclization) of **1** (and also **5** and **19**) indicates that the mechanism involves activation of the benzyl alcohol moiety by the phenol, which results in overall cyclization *and* photosolvolysis. The plot of photocyclization quantum yield vs pH for **1** (Figure 6) is strong evidence for the involvement of the phenol moiety. In fact, Figure 6 implicates the involvement of the excited-state *phenolate* in the mechanism. Considering that photocyclization involves one photon, although secondary photochemistry does take place, a mechanism of reaction is proposed below.

There are three mechanistic regimes depending on the pH of the medium, as shown in Figure 6. Each mechanistic regime will be discussed in turn. To start, consider the photocyclization mechanism in the pH range −1 to 9. In this acidity region, **1** exists as the phenol. Photolysis of **1** leads to an excited singlet state that is more acidic and has a tendency to twist to a more planar geometry. We propose (Scheme II) that initially excited **1** twists to a more planar geometry (which should be very fast since it is only a torsional motion) followed by deprotonation (which would also be fast) to give the phenolate form, which remains on the excited singlet-state surface. A large number of phenols and related compounds are known to undergo efficient adiabatic ionization of the phenolic proton[20] so the assumption of an adiabatic loss of proton with torsional motion is not unrealistic. The twisting of the biphenyl can in principle result in a cis and a trans isomer. The relative yield of these isomers is unknown. We propose that the subsequent step is charge transfer of the phenolate ion to the adjacent benzyl alcohol ring, which results in overall dehydroxylation to generate two *o*-quinonemethide type intermediates **20**. This step probably results in electronic deactivation. That is, the cis and trans *o*-quinonemethides **20** (Scheme II) are generated in the ground state. Again, the ratio of the cis and trans forms is unknown. Both forms may be trapped by external nucleophiles ($H_2O$ or MeOH) at the benzylic carbon; only the cis form can cyclize to give the pyran **7**.

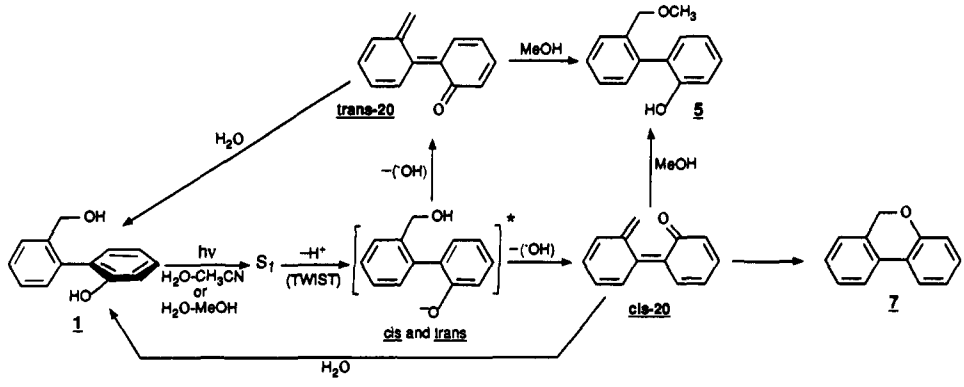
In the pH range above 10, **1** exists exclusively as the phenolate in the ground state. Excitation of this form leads to a phenolate ion in the excited state that need only twist to reach the precursor to the *o*-quinonemethides **20**. The higher photocyclization quantum yield observed at pH > 10 is readily explained because there are now fewer nonproductive deactivational pathways that the molecule has to complete with in order to reach the essential reactive intermediates (viz. *o*-quinonemethides **20**).

In the acid region below $H_0 = -1$, $\Phi$ does not reach zero. In addition, we have shown that **1** *does* photocyclize to **7** even at acidities stronger than $H_0 = -1$. Clearly another distinct mechanistic regime for photocyclization is operative at these acidities. Since the phenol moiety would not be deprotonated in $S_1$ at these acidities (recall $pK_a(S_1) \approx 1$), a reasonable mechanism for reaction is that shown in eq 4. This mechanism was shown not to be operative in the pH 0–13 region. However, in stronger acid, we have shown that both **2** and **4** undergo photosolvolysis; that is, the corresponding methyl ether products were observed on photolysis in MeOH–$H_2SO_4$ mixtures. A similar reaction would be expected for **1**, which because of the adjacent phenol moiety would result in photocyclization. This aspect of the mechanism is under additional investigation.

**Summary.** Mechanistic studies of a new photochemical reaction of biphenyl systems that results in efficient overall cyclization has been reported. The necessary structural features required for reaction have been delineated. A mechanism of reaction involving the phenolate ion in $S_1$ as the precursor of an *o*-quinonemethide type intermediate has been proposed. This electrophilic *o*-quinonemethide intermediate can either cyclize to the pyran or be trapped (at the benzylic carbon) by an external nucleophile. This mechanism is supported by product studies and fluorescence measurements. To better understand the mechanism of this re-

(20) Ireland, J. F.; Wyatt, P. A. H. *Adv. Phys. Org. Chem.* **1976**, *12*, 131.

Scheme II




action, additional studies aimed at characterizing transient intermediates proposed in this work by laser flash photolysis as well as exploring the scope and mechanistic implications of this type of reaction are in progress.

## Experimental Section

**General.** Preparative or semipreparative photolyses were carried out on Rayonet RPR 100 photochemical reactors equipped with 254-nm lamps (or 350-nm lamps for sensitization experiments). $^1$H NMR spectra were taken on a Perkin-Elmer RS32 (90 MHz) or a Bruker WM 250 (250 MHz) instrument in $CDCl_3$ unless otherwise noted. Gas chromatography was carried out on a Varian 3700 instrument with a Hewlett-Packard 3390A integrator with a DB-5 capillary column. Mass spectra were taken on a Finnigan 3300 instrument. Melting points were obtained on a Koefler hot-stage microscope and are uncorrected. UV spectra were recorded on a Perkin-Elmer Lambda 4B or a Pye-Unicam 800 spectrophotometer. IR spectra were taken on NaCl plates with a Perkin-Elmer 283 instrument.

**Crystal-Structure Analysis.** The experimental details are listed in Table I. A Nonius diffractometer using $\omega/2\theta$ scan was used to collect the data for **1**. A total of 900 reflections were collected and 699 ($I > 1.5\sigma(I)$) were used in the structure refinement. A Picker four-circle diffractometer using $\theta/2\theta$ scan was used to collect the data for **6**. A total of 1156 reflections were collected and used for structure refinement. Both structures were solved on MULTAN[21] and refined by using least squares on SHELX-76.[22] Illustrations were drawn on ORTEP.[23]

**Materials. 2′-Hydroxybiphenyl-2-carboxylic Acid Lactone (8).** This substance was prepared via the procedure of Moore et al.[24] To a stirred solution of biphenyl-2-carboxylic acid (10 g, 50.5 mmol) (from Aldrich) in acetic acid (150 mL) was carefully added a suspension of chromium trioxide ($CrO_3$) (40 g, 400 mmol) in 80 mL of distilled $H_2O$. The reaction mixture was refluxed at 95–105 °C for 45 min and then poured into 200 mL of cold water. The combined organic extracts (by 3 × 150 mL $CH_2Cl_2$) were washed with saturated aqueous $NaHCO_3$ to remove the unreacted starting material and then dried over $MgSO_4$. Removal of the solvent under reduced pressure gave a white solid powder. Recrystallization of this powder from 95% EtOH afforded white crystals (3.96 g, 40%): mp 90–92 °C (lit.[24] mp 92.5 °C); $^1$H NMR $\delta$ 7.25–8.35 (m, 8 H, ArH); MS (EI) $m/z$ (relative intensity) 196 ($M^+$) (100), 168 ($M^+$ – CO) (38), 139 (44); IR ($cm^{-1}$) (in mineral oil on NaCl plates) 3050 (w), 1720 (s), 1598 (m), 1550 (m), 1500 (m), 1300 (m).

**2-(2′-Hydroxyphenyl)benzyl Alcohol [2′-Hydroxy-2-biphenylmethanol] (1).** This was prepared from 2′-hydroxybiphenyl-2-carboxylic acid lactone (**8**) according to the procedure of Devlin:[9a] mp 134–135 °C (lit.[9a] mp 137 °C); $^1$H NMR $\delta$ (acetone-$d_6$) 4.05 (t, $J$ = 6 Hz, exchangeable with $D_2O$, 1 H, OH), 4.48 (d, $J$ = 6 Hz, 2 H, $ArCH_2O$), 6.80–7.80 (m, 7 H, ArH), 7.60 (m, 1 H, ArH), 8.17 (s, exchangeable with $D_2O$, 1 H, ArOH); MS (EI) $m/z$ 182 ($M^+ - H_2O$) (14), 181 (100), 171 (10).

**2-(2′-Methoxyphenyl)benzyl Alcohol (4).** To a stirred suspension of anhydrous $K_2CO_3$ (1.4 g, 10 mmol) and methyl iodide (1.4 mL, 15 mmol) in dry acetone (20 mL) was added alcohol **1** (2 g, 10 mmol). The reaction mixture was refluxed for 3 h, cooled to room temperature, and then filtered by gravity filtration. Removal of the acetone gave a colorless oil that was purified by column chromatography (silica, $CH_2Cl_2$): $^1$H NMR $\delta$ 3.70 (s, 3 H, $OCH_3$), 2.40 (broad, exchangeable with $D_2O$, 1 H, $CH_2OH$), 4.42 (s, 2 H, $ArCH_2O$), 6.93–7.61 (m, 8 H, ArH); MS (EI) $m/z$ (relative intensity) 214 ($M^+$) (10), 181 (16), 165 (6).

**2-(2′-Hydroxyphenyl)benzyl Methyl Ether (5).** To a stirred solution of **1** (0.5 g, 2.5 mmol) in 100 mL of MeOH was added 2 mL of concentrated $H_2SO_4$. The mixture was refluxed overnight and quenched with 20 mL of 1 M NaOH. Extraction with $CH_2Cl_2$ and subsequent evaporation of the solvent gave an oil that was purified by preparative TLC (silica, $CH_2Cl_2$): $^1$H NMR $\delta$ 3.32 (s, 3 H, $OCH_3$), 4.26 (s, 2 H, $ArCH_2O$), 5.12 (broad, 1 H, ArOH), 6.95–7.51 (m, 8 H, ArH); MS (EI) $m/z$ (relative intensity) 214 ($M^+$) (12), 181 (100).

**2-(2′-Hydroxyphenyl)-α,α-dimethylbenzyl Alcohol (6).** Methylmagnesium bromide reagent was prepared from methyl bromide (8 mL, 16 mmol) and Mg (2 g, 83.5 mmol) in 30 mL of anhydrous ether. This solution was added dropwise to a solution of **8** (4 g, 20 mmol) in 150 mL THF. The combined solution was refluxed for 3 h and quenched with aqueous $KH_2PO_4$. The combined organic extracts (3 × 150 mL $CH_2Cl_2$) were dried over $MgSO_4$ and evaporated to give a solid, which was recrystallized from toluene: mp 124–125 °C, yield 3.2 g (70%); $^1$H NMR ($CD_3Cl$/DMSO) $\delta$ 1.32 (s, 3 H, $CH_3$), 1.57 (s, 3 H, $CH_3$), 3.81 (broad, exchangeable with $D_2O$, 1 H, $C(CH_3)_2OH$), 6.90–7.40 (m, 7 H, ArH), 7.60–7.70 (m, 1 H, ArH), 7.82 (broad, exchangeable with $D_2O$, 1 H, ArOH); MS (CI) $m/z$ (relative intensity) 210 ($M^+ - H_2O$) (100); IR ($cm^{-1}$) (in mineral oil on NaCl plates) 3290 (s, broad), 3050 (w), 1580 (m), 1400 (m), 1380 (s), 1200 (s), 1152 (s).

**6*H*-Dibenzo[*b*,*d*]pyran (7).** This was prepared from 2′-hydroxybiphenyl-2-carboxylic acid lactone (**8**) according to the procedure of Devlin:[9a] $^1$H NMR $\delta$ 5.08 (s, 2 H, $ArCH_2O$), 6.90–7.40 (m, 6 H, ArH), 7.68 (m, 2 H, ArH); MS (CI) $m/z$ 183 ($M^+$) (10) 182 (78), 181 (100), 152 (25).

**6,6-Dimethyl-6*H*-dibenzo[*b*,*d*]pyran (11).** A suspension of lactone **8** (4 g, 20 mmol) in 100 mL of THF was added over 10 min to a solution of 1 M methylmagnesium bromide in 40 mL of THF. The solution was refluxed for 3 h and quenched by pouring it into cold aqueous $H_2SO_4$ (15 mL of concentrated $H_2SO_4$ and 100 mL of ice). The combined ether extracts were evaporated to give a colorless oil, which was further purified by column chromatography (silica, hexanes), yield 3.5 g (83%): $^1$H NMR ($\delta$) 1.59 (s, 6 H, $CH_3$), 6.95–7.35 (m, 6 H, ArH), 7.70–7.80 (m, 2 H, ArH); MS (EI) $m/z$ (relative intensity) 210 ($M^+$) (6), 196 (15), 195 ($M^+ - CH_3$) (100). The $^1$H NMR spectrum was identical with that reported by Dewar et al.[25] for this compound.

**2-(2′-Hydroxyphenyl)-α,α-dimethylbenzyl Methyl Ether (18).** To a stirred solution of **6** (0.2 g, 0.9 mmol) in 100 mL of MeOH was added 20 mL of pH 1 $H_2SO_4$ solution and left stirring at room temperature overnight. This was quenched by adding cold water and extracted with 2 × 150 mL $CH_2Cl_2$. On evaporation of the solvent, GC and $^1$H NMR analysis showed ca. 3% **18**, the rest being **6** and pyran **11**. It is clear that alcohol **6** is more prone to thermal cyclization than **1**. The methyl ether **18** was characterized by GC/MS and $^1$H NMR: $^1$H NMR (partial) $\delta$ 1.25 (s, 6 H, $CH_3$), 3.05 (s, 3 H, $OCH_3$); GC retention time ($t_r$) (column temperature 180 °C) 4.83 min for **18** and 4.74 min for **6**; MS (CI) $m/z$ (relative intensity) 210 ($M^+$ – MeOH).

**2-(2′-Hydroxyphenyl)benzyl Chloride (19).** This compound was prepared from alcohol **1** by use of a method developed by Masada and Murotani.[26] To a solution of 20 mL of concentrated HCl was added a

(21) Main, P. *Multan: Programme for the Automatic Solution of Crystal Structures from X-ray Diffraction Data by Multiple Starting Point Tangent Formula*; University of York, England, 1978.

(22) Sheldrick, G. M. SHELX-76, *Program for Crytal Structure Determinations*; University of Cambridge: Cambridge, England, 1976.

(23) Johnson, C. K. ORTEPII, Report ORNL-5138; Oak Ridge National Laboratory: Oak Ridge, TN, 1976.

(24) Moore, G. W.; Murray, H. A.; Taylor, C. M. B. *Tetrahedron* **1957**, *1*, 259.

(25) Dewar, P. S.; Forrester, A. R.; Thomson, R. H. *J. Chem. Soc. C* **1971**, 3950.

mixture of alcohol **1** (0.5 g, 2.5 mmol) and lithium chloride (1 g) at 0 °C. The reaction mixture was warmed up to 50 °C and stirred until the solids completely dissolved (2 h). After heating at 60 °C for 6 h, the reaction mixture was quenched by adding 100 mL of $H_2O$. The combined organic extracts (3 × 100 $CH_2Cl_2$) were washed with ethylene glycol (3 × 50 mL) to remove HCl and dried over $MgSO_4$, which on evaporation gave **19** as a colorless oil (0.4 g, 73%). This was purified by preparative TLC (silica gel, $CH_2Cl_2$): $^1H$ NMR $\delta$ 4.41 (s, 2 H, $CH_2Cl$), 5.0 (broad, exchangeable with $D_2O$, 1 H, ArOH), 6.90–7.63 (m, 8 H, ArH); MS (CI) $m/z$ 182 ($M^+$ – HCl).

**Product Studies.** In general, 20–200-mg samples were dissolved in the appropriate solvent or solvent mixture (3–200 mL) and irradiated in either (i) 3.0-mL Suprasil quartz cuvettes, (ii) 20-mL quartz tubes, or (iii) 200-mL quartz tubes, depending on the scale of the experiment. For analytical-scale runs by GC, only the 3.0- or 20-mL volume scales were employed, whereas for preparative runs, the 200-mL tubes were used. Photolyses using the 200-mL tubes were cooled by using a cold-finger (tap water) along with continuous purging with a stream of argon via a long fine metal needle. Photolyses using the smaller 20-mL tubes or cuvettes were carried out by using a merry-go-round apparatus and were cooled by air. These samples were purged with a stream of argon and sealed with Teflon stoppers or stopcocks prior to photolysis.

**Photolysis of 1 in 1:1 $H_2O$–$CH_3CN$.** Preparative photolysis of **1** was carried out in the following fashion. A solution of **1** (200 mg) in 1:1 $H_2O$–$CH_3CN$ (200 mL) was irradiated at 254 nm for 1.5 h. After photolysis, 200 mL of $H_2O$ was added and the solution saturated with NaCl. The solution was then extracted with 3 × 150 mL $CH_2Cl_2$. The combined extracts were dried over $MgSO_4$ and evaporated. Product analysis was carried out using $^1H$ NMR and GC. Final product identification was achieved by isolation via preparative TLC (silica, $CH_2Cl_2$) to yield 150 mg (82.5%) of **7**.

For analytical runs, a solution of 20 mg of **1** in 1:1 $H_2O$–$CH_3CN$ (100 mL) was irradiated and aliquots were taken for analysis by GC (after workup). The GC retention times ($t_r$) were 4.53 and 5.34 min for **7** and **1**, respectively (column temperature 180 °C).

**Photolyses of 1 in 100% MeOH.** A solution of 200 mg of **1** in 200 mL of MeOH was photolyzed at 254 nm for 2 h. The solvent was removed and the photolysate analyzed by $^1H$ NMR and GC, which indicated only **7** and **5** as photoproducts, in a 55:45 ratio. To confirm their structures, they were separated by preparative TLC (silica, $CH_2Cl_2$) and identified by comparison with authentic samples. Analytical runs were carried out as described above, using GC for analysis.

**Photolysis of 2–4 in 1:1 $H_2O$–$CH_3CN$.** A solution of 100 mg of **2–4** in 1:1 $H_2O$–$CH_3CN$ (200 mL) was irradiated for 2 h at 254 nm. On workup (procedure described above), the product mixtures were analyzed by $^1H$ NMR and GC. In the case of **3** and **4**, no photoproducts were detected and the starting materials were recovered unchanged. In the case of **2**, a photoisomerized photoproducts was formed and identified as *m*-phenylbenzyl alcohol:[9b] $^1H$ NMR ($\delta$) 1.85 (broad, exchangeable with $D_2O$, 1 H, OH), 4.71 (s, 2 H, $ArCH_2O$), 7.30–7.60 (m, 8 H, ArH).

**Photolysis of 2 and 4 in 1:1 20% $H_2SO_4$–MeOH ($H_0$ of Aqueous Portion ≈ −1).** Solutions of **2** and **4** were irradiated in 1:1 MeOH–20% $H_2SO_4$ at 254 nm for 2 h. After neutralization of the solution with aqueous NaOH, the general workup procedure already described was used. The corresponding methyl ethers were isolated by preparative TLC and were the only products. Dark control reactions showed no thermal solvolysis. 2-Phenylbenzyl methyl ether was formed from **2** (≈30%): $^1H$ NMR $\delta$ 3.25 (s, 3 H, $OCH_3$), 4.25 (s, 2 H, $ArCH_2O$), 7.25–7.50 (m, 9 H, ArH). 2-(2′-Methoxyphenyl)benzyl methyl ether was formed from **4** (~40%): $^1H$ NMR $\delta$ 3.25 (s, 3 H, $ArCH_2OCH_3$), 3.7 (s, 3 H, $ArOCH_3$), 4.30 (s, 2 H, $ArCH_2O$), 6.95–7.55 (m, 8 H, ArH).

**Photolysis of 5 in 100% MeOH.** A solution of 100 mg of **5** in 200 mL of MeOH was irradiated for 2 h at 254 nm. The product mixture showed formation of **7** (50%) and substrate **5** (50%). Extended photolysis increased the yield of **7** to a maximum of 55%, with recovered **5** (45%). This ratio is believed to be the photostationary state, as confirmed by photolysis of **7** in 100% MeOH below.

**Photolysis of 6 in 1:1 $H_2O$–$CH_3CN$.** For preparative runs, a solution of 200 mg of **6** in 1:1 $H_2O$–$CH_3CN$ (200 mL) was irradiated for 2 h. After the general workup described above, the product mixture was separated by preparative TLC (silica, 1:1 hexanes–$CH_2Cl_2$). Four photoproducts were isolated and identified by GC/MS and $^1H$ NMR: **11** (10%), $t_r$ = 4.57 (180 °C), spectroscopic data identical with an authentic sample; **12** (7%), $t_r$ = 3.82, $^1H$ NMR $\delta$ 1.68 (s, 3 H, =D—$CH_3$), 5.05 (m, 2 H, $=CH_2$), 5.38 (broad, exchangeable with $D_2O$, 1 H, ArOH), 6.80–7.30 (m, 7 H, ArH), MS (CI) $m/z$ 211 ($M^+$ + 1); **13** (40%), $t_r$ = 8.00, $^1H$ NMR $\delta$ 2.73 (s, 3 H, $ArCH_3$), 7.60–7.80 (m, 6 H, ArH), 8.15 (m, 1 H, ArH), 8.75 (m, 2 H, ArH), MS (CI) $m/z$ 193 ($M^+$ + 1); **14** (25%), $t_r$ = 7.38, $^1H$ NMR $\delta$ 1.24 (d, $J$ = 8 Hz, 3 H, $CH_3$), 2.50–2.90 (m, 3 H, CH—$CH_2$), 5.38 (broad, exchangeable with $D_2O$, 1 H, ArOH), 6.80–7.35 (m, 7 H, ArH), MS (CI) $m/z$ 211 ($M^+$ + 1). All $^1H$ NMR data reported for **12–14** are in agreement with those reported by Bowd et al.[12a]

For analytical runs, a solution of 20 mg in 100 mL of 1:1 $H_2O$–$CH_3CN$ was irradiated and aliquots were removed and analyzed by GC after workup. Yields of the various products were calculated from uncorrected GC integration areas. Since all the products have the same number of carbons, this would not introduce any significant errors in the product ratios.

**Photolysis of 6 in 100% MeOH.** A solution of 100 mg of **6** in 100 mL of MeOH was irradiated at 254 nm for 5–10 min. After removal of the solvent, the product mixture was analyzed by $^1H$ NMR. In addition to formation of **11** and **12** (and subsequently **13** and **14**), the methanol-trapping product **18** was also observed but in low yields (<10%) (as identified by GC/MS and its characteristic methoxy singlet at $\delta$ 3.05).

**Photolysis of 7 in 100% MeOH and 1:1 $H_2O$–$CH_3CN$.** Irradiation at 254 nm of a solution of 20 mg of **7** in 100 mL of MeOH gave **5** as the only product. The reaction was followed by GC by removing aliquots at different photolysis times. After exhaustive photolysis (>2 h), the ratio of **7** ($t_r$ = 4.52): **5** ($t_r$ = 4.40) was 55:45, by GC integration. In a similar experiment with **7** in 1:1 $H_2O$–$CH_3CN$, the only product was **1** ($t_r$ = 5.34), but in very low yield (≈2% after exhaustive photolysis).

**Photolysis of 11 in 100% MeOH and $H_2O$–$CH_3CN$.** By using the same procedure as above, photolysis of **11** in either 100% MeOH or 1:1 $H_2O$–$CH_3CN$ was followed by GC. All the products observed have already been characterized with known retention times. When photolyzed in 100% MeOH, **11** gave low yields (<10%) of **18**, in addition to **12–14**.

**Photolysis of 19 in 1:1 $H_2O$–$CH_3CN$.** Two products (**7** and **1**) were observed on photolysis of **19** in 1:1 $H_2O$–$CH_3CN$, with **7** being the major product (**7**:**1** = 95:5) at 60% conversion.

**Triplet-State Sensitization.** In a typical experiment, 20 mg of **1** and 3 g of sensitizer (sodium benzophenone-2-carboxylate or sodium acetylbenzenesulfonate, purchased from Aldrich) were dissolved in 100 mL of 1:1 $H_2O$–$CH_3CN$ (pH 7). After deaeration with an argon purge, the solution was irradiated at 350 nm for 10–30 min. At 350 nm, only the sensitizer absorbed irradiation. After photolysis, the solution was saturated with NaCl and extracted several times with $CH_2Cl_2$. The combined organic layers were then washed with bicarbonate solution to remove residual sensitizer and evaporated, and the residue was analyzed by GC and $^1H$ NMR. In all runs, no photocyclization product (**7**) was observed and **1** was recovered.

**Quantum Yield Measurements.** Quantum yields were measured by using 280-nm excitation from the output of an Oriel 200-W Hg lamp filtered through an Applied Photophysics monochromator and a 254–400 bandpass filter. Solutions (~$10^{-3}$ 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.[27] After photolysis, the sample was extracted several times with $CH_2Cl_2$ and conversions (kept <15%) were analyzed by GC. Excellent material balances were observed, as determined by a xanthene external standard. GC responses of starting materials and products were essentially identical.

**Fluorescence Measurements.** Fluorescence emission spectra (uncorrected) were taken in 3.0-mL quartz cuvettes at ~$10^{-4}$ M on a Perkin-Elmer MPF 66 spectrophotometer at ambient temperature ($\lambda_{excit}$ = 265 nm). Standardized HCl or $H_2SO_4$ solutions were used for acid-quenching experiments. The fluorescence quantum yield of **1** in neutral 1:1 $H_2O$–$CH_3CN$ was measured relative to naphthalene[28] in cyclohexane ($\Phi_f$ = 0.23) as a secondary fluorescence standard. Optical densities at $\lambda_{excit}$ = 265 nm were matched prior to measurement. Fluorescence lifetimes 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 the excitation source. Decays were analyzed on software supplied by PTI. All samples for fluorescence measurements were deaerated by argon purging prior to measurement.

**Acknowledgment** is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research. Additional support was provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada. The University of Victoria provided a graduate fellowship to C.-G.H. We also thank Deepak

(26) Masada, H.; Murotoni, Y. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 1181.

(27) Hatchard, C. G.; Parker, C. A. *Proc. R. Soc., London, A* **1956**, *235*, 518.

(28) Eaton, D. F. *Pure Appl. Chem.* **1988**, *60*, 1107.

Shukla for measuring the single-photon fluorescence lifetimes.

**Registry No.** 1, 134906-85-7; 2, 2928-43-0; 3, 90-43-7; 4, 134906-89-1; 5, 134906-86-8; 6, 134906-87-9; 7, 229-95-8; 8, 2005-10-9; 11, 29574-51-4; 12, 134906-90-4; 13, 883-20-5; 14, 52978-94-6; 18, 134906-91-5; 19, 134906-88-0; *cis*-20, 134906-92-6.

**Supplementary Material Available:** Tables of positional parameters, anisotropic thermal parameters, bond lengths, and angles (15 pages); tables of observed and calculated structure factors (11 pages). Ordering information is given on any current masthead page.

# Crystal Structures of Self-Aggregates of Insoluble Aliphatic Amphiphilic Molecules at the Air–Water Interface. An X-ray Synchrotron Study

**D. Jacquemain,[†] F. Leveiller,[†] S. P. Weinbach,[†] M. Lahav,[†] L. Leiserowitz,*[,†] K. Kjaer,[‡] and J. Als-Nielsen*[,‡]**

*Contribution from the Structural Chemistry Department, Weizmann Institute of Science, Rehovot 76100, Israel, and Physics Department, Risø National Laboratory, DK4000 Roskilde, Denmark.* *Received February 14, 1991*

**Abstract:** Uncompressed insoluble amphiphilic molecules possessing linear hydrocarbon chains $C_nH_{2n+1}X$ ($n$ = 23, 30, 31, X = OH; $n$ = 29, X = COOH; and $n$ = 19, X = $CONH_2$) spontaneously form large two-dimensional (2-D) crystalline clusters over pure water at low temperature (5 °C). These 2-D crystallites were detected and their structures were solved using grazing incidence X-ray diffraction (GID). Their packing arrangements are described in terms of 2-D space-group symmetry and hydrocarbon-chain packing. All the crystal structures display rectangular unit cells containing two molecules that are probably related by glide symmetry in the 2-D space group *pg* for the alcohol (X = OH) and the acid (X = COOH) and by translation symmetry in the 2-D space group *p*1 for the amide (X = $CONH_2$). The alcohol molecules are tilted by 8–11° from the vertical toward next-nearest neighbors, the tilt angle being dependent on the chain length. The amide and the acid molecules are tilted toward nearest neighbors by 18° and 26°, respectively. The positional correlation lengths of the crystallites were found to be anisotropic; they extend over only 35–95 spacings parallel to the molecular tilt direction, but over 135–270 spacings perpendicular to it. The similarity of chain packing in the 2-D crystallites and in three-dimensional (3-D) crystals of aliphatic amphiphilic molecules is clearly established. These crystallites may therefore, on the water surface, mimic crystallization mechanisms observed in 3-D systems.

## Introduction

Evidence for the formation of self-organized two-dimensional (2-D) crystals composed of amphiphilic molecules at the air–water interface has, until recently, been indirect. For example, surface tension and oriented crystallization studies of *soluble* hydrophobic α-amino acids have brought forth evidence that they not only accumulate spontaneously but also form two-dimensional crystalline aggregates (crystallites) at the solution surfaces.[1-3] Studies of oriented crystallization extended to *insoluble* amphiphilic α-amino acid molecules forming Langmuir monolayers also brought evidence for the spontaneous formation of crystallites at the solution surface, even when the amphiphilic molecular concentration at the surface is very low.[3b] Epifluorescence measurements gave a visual confirmation of the spontaneous aggregation of insoluble amphiphilic molecules at the water surface and furnished some information on the orientational order and on the morphology of the aggregates on the micron level.[4] However, these studies provide no direct information on the crystallite size and structure on the molecular level. The newly developed synchrotron X-ray surface technique of grazing incidence X-ray diffraction[5] (GID) is a powerful tool for exploring this field since it allows for the detection of crystallites formed by insoluble amphiphilic molecules and for the determination of their size and structure almost at the atomic level. We were not able to detect crystalline self-aggregation of uncompressed monolayers of α-amino acid surfactants with hydrocarbon chains at room temperature.[5b] However, we did observe the spontaneous formation of crystallites of the α-amino acid amphiphile $CF_3(CF_2)_9(CH_2)_2OCOCH_2CH(NH_3^+)CO_2^-$ at room temperature[6] with a lateral ordering range exceeding 1500 Å. More recently, crystalline self-aggregation has been observed by GID for the fluorinated acid[7] $C_{10}F_{21}CH_2COOH$. It was concluded for both systems that nearly all the molecules are in the crystalline phase.

Here, we report GID results from insoluble aliphatic amphiphilic molecules in the uncompressed state at the air–water interface. Monolayers with hydrocarbon chains proved to be less crystalline than those with fluorocarbon chains in their uncom-

[†] Weizmann Institute of Science.
[‡] Risø National Laboratory.

(1) Weissbuch, I.; Addadi, L.; Berkovitch-Yellin, Z.; Gati, E.; Lahav, M.; Leiserowitz, L. *Nature* **1984**, *310*, 161.
(2) Weissbuch, I.; Frolow, F.; Addadi, L.; Lahav, M.; Leiserowitz, L. *J. Am. Chem. Soc.* **1990**, *112*, 7718.
(3) (a) Landau, E. M.; Levanon, M.; Leiserowitz, L.; Lahav, M.; Sagiv, J. *Nature* **1985**, *318*, 353. (b) Landau, E. M.; Grayer Wolf, S.; Levanon, M.; Leiserowitz, L.; Lahav, M.; Sagiv, J. *J. Am. Chem. Soc.* **1989**, *111*, 1436.
(4) (a) Von Tscharner, V.; McConnell, H. M. *Biophys. J.* **1981**, *36*, 409. (b) Lösche, M.; Möhwald, H. *Rev. Sci. Instrum.* **1984**, *55*, 1968. (c) Moore, G. B.; Knobler, C. M.; Akamatsu, S.; Rondelez, F. *J. Phys. Chem.* **1990**, *94*, 4588.
(5) (a) Kjaer, K.; Als-Nielsen, J.; Helm, C. A.; Laxhuber, L. A.; Möhwald, H. *Phys. Rev. Lett.* **1987**, *58*, 2224. (b) Grayer Wolf, S.; Leiserowitz, L.; Lahav, M.; Deutsch, M.; Kjaer, K.; Als-Nielsen, J. *Nature* **1987**, *328*, 63. (c) Barton, S. W.; Thomas, B. N.; Flom, E. B.; Rice, S. A.; Lin, B.; Peng, J. B.; Ketterson, J. B.; Dutta, P. *J. Chem. Phys.* **1988**, *89*, 2257. (d) Helm, C. A.; Möhwald, H.; Kjaer, K.; Als-Nielsen, J. *Biophys. J.* **1987**, *52*, 381. (e) Kjaer, K.; Als-Nielsen, J.; Helm, C. A.; Tippman-Krayer, P.; Möhwald, H. *J. Phys. Chem.* **1989**, *93*, 3200.
(6) Jacquemain, D.; Grayer Wolf, S.; Leveiller, F.; Leiserowitz, L.; Lahav, M.; Deutsch, M.; Kjaer, K.; Als-Nielsen, J. *J. Am. Chem. Soc.* **1990**, *112*, 7724.
(7) Barton, S. W.; Coudort, Rondelez, F.; Lin, B.; Novak, Rice, S. A. Manuscript in preparation.

0002-7863/91/1513-7684$02.50/0 