Substituent effects in the intramolecular photoredox reactions of benzophenones in aqueous solution

Nikola Basarić, Devin Mitchell, and Peter Wan

Abstract: A number of α-hydroxy-3-benzylbenzophenones **7**–**11** have been synthesized for the purpose of studying the effect of a phenyl substituent on the intramolecular photoredox reaction of 3-(hydroxymethyl)benzophenone (**5**) discovered in our laboratory. This latter compound was found to undergo a unimolecular (formal) intramolecular redox reaction upon photolysis in aqueous acid that results in clean reduction of the benzophenone ketone (to secondary alcohol) and oxidation of the alcohol to aldehyde. Three of the phenyl-substituted compounds with simple phenyl (**7**), *p*-methylphenyl (**8**), and *p*-methoxyphenyl (**9**) were found to undergo the acid-catalyzed intramolecular photoredox reaction with the observation that **9** also undergoes a residual photoredox reaction that is not acid-mediated and may involve initial photoinduced electron transfer, which is supported by LFP data. The *m*-methoxyphenyl (**10**) compound did not undergo the reaction. The trend in observed relative reactivity may be partially rationalized by examining changes in molecular orbital coefficients observed in the calculated HOMOs and LUMOs. The photoredox reaction has also been applied twice in succession in a single compound **11**, demonstrating that the photoredox reaction may be useful for sequential photoredox reactions in a multifunctional compound.

Key words: intramolecular photoredox, acid catalysis, meta effect, benzophenone photochemistry.

Résumé : On a synthétisé un certain nombre de α-hydroxy-3-benzylbenzophénones (**7**–**11**) pour pouvoir étudier l'effet d'un substituant phényle sur la réaction de photoredox intramoléculaire de la 3-(hydroxyméthyl)benzophénone (**5**) qui a été découverte dans notre laboratoire. On a trouvé que lorsque ce dernier composé en solution acide aqueuse est soumis à une photolyse, il subit une réaction redox intramoléculaire qui conduit à une réduction propre du groupement carbonyle de la benzophénone en alcool secondaire avec oxydation concomitante de l'alcool en aldéhyde. On a observé que, en solution aqueuse acidulée, trois des composés substitués par un groupe phényle, soit le dérivé phényle non substitué (**7**), le *p*-méthylphényle (**8**) et le *p*-méthoxyphényle (**9**), subissent la réaction photoredox intramoléculaire qui est accompagnée dans le cas du produit **9** d'une réaction photoredox résiduelle qui n'est pas catalysée par les acides et qui peut impliquer un transfert initial d'électron qui est photoinduit et cette hypothèse est supporter par des données de « LPF ». Le composé méthoxyphényle (**10**) ne subit pas la réaction. La tendance dans les réactivités relatives observées peut être partiellement expliquée par un examen des changements dans les coefficients d'orbitales moléculaires qui sont observés dans les valeurs calculées des orbitales moléculaires HO et BV. On a aussi appliqué la réaction photoredox deux fois en succession à un composé unique, **11**; ce résultat démontre que la réaction photoredox pourrait être utile pour des réactions photoredox séquentielles dans un composé multifonctionnel.

Mots-clés : photoredox intramoléculaire, catalyse acide, effet méta, photochimie des benzophénones.

[Traduit par la Rédaction]

Introduction

The photochemistry and photophysics of benzophenone (**1**) and its derivatives have been studied for over a century (1, 2). Indeed, benzophenone photoreduction was one of the first photoreactions described in the literature (3). Despite the many studies on this reaction, it was not until about 60 years later that the mechanism was shown to proceed via the triplet excited state (4, 5). Although many studies have examined benzophenone (**1**) photoreduction in various organic solvents, fewer studies have examined its photochemical and photophysical behavior in aqueous solution. It is known that the benzophenone triplet excited state is quenched by acid. This was first reported by Ledger and Porter (6) who noted that the phosphorescence of benzophenone (**1**) was quenched by added protons, although the detailed mechanism was not understood at that time. Initially, it was thought that the quenching was due to the formation of the protonated triplet **2** (protonation at the carbonyl) and Wyatt and co-workers (7, 8) assigned a pK_a of 1.5 ± 0.1 for the protonated triplet excited state using Förster cycle analysis. That is, the benzophenone triplet is more basic by sev-

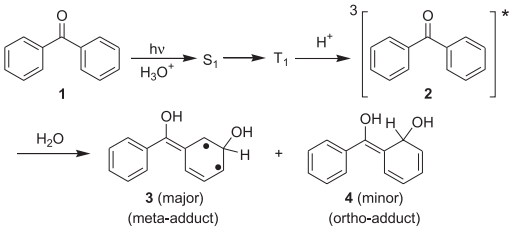
Received 13 June 2007. Accepted 3 July 2007. Published on the NRC Research Press Web site at canjchem.nrc.ca on 1 August 2007.

N. Basarić,[1] D. Mitchell, and P. Wan.[2] Department of Chemistry, University of Victoria, Victoria, BC V8W 3V6, Canada.

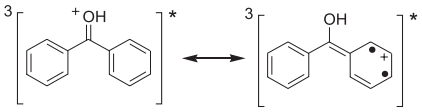
[1]On leave from the Ruder Boskovic Institute, Zagreb, Croatia.
[2]Corresponding author (e-mail: pwan@uvic.ca).

 doi:10.1139/V07-081

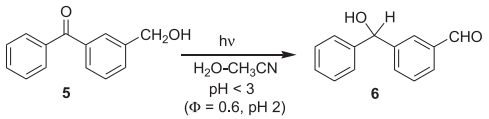
eral orders of magnitude (at the carbonyl oxygen) compared with the ground state ($pK_a(S_o) = -5.7$ (7)). In a recent study, Wirz and co-workers (9) established that protonation (at the carbonyl) of triplet benzophenone results in an overall *photohydration* reaction, to give water-adducts **3** and **4** with a preference for **3**, i.e., hydration at the meta position (eq. [1]). This reaction was unexpected and has probably missed detection in the past because of the instability of the hydration products, which readily revert back to **1**. In addition, Wirz and co-workers (9) assigned a pK_a of –0.4 for the protonated triplet excited state; thus, the triplet is somewhat less basic than originally estimated by Wyatt and co-workers (7, 8).

[1] 

The mechanism (9) of photohydration presumably involves initial protonation of the carbonyl oxygen of triplet excited benzophenone, to generate an excited triplet state conjugate acid that has its positive charge significantly delocalized to the ortho and meta positions of the benzene ring (e.g., as shown in eq. [2]), as would be anticipated based on the Zimmerman "ortho-meta" effect for benzene ring site activation in photochemical reactions (10, 11). Attack by water at these sites of positive charge would lead to the observed hydration products, which upon deactivation to their ground states would not be expected to be long-lived and would readily return to benzophenone (**1**) by dehydration (and re-aromatization).

[2] 

Although the described acid-catalyzed photohydration of benzophenone itself reported by Wirz and co-workers (9) gave no isolable *stable* product, it seemed reasonable to assume that the protonation of triplet excited benzophenone (**1**) might lead to other acid-catalyzed chemistry still to be discovered considering the known range and diversity of chemistry for ground state carbonyl compounds that are acid-catalyzed. Indeed, Wirz and co-workers (9) reported the acid-catalyzed photohydrolysis of *m*-fluoroacetophenones and benzophenones to give the corresponding phenols as proceeding via a protonated triplet. We recently reported two photochemical reactions of benzophenones that require acid-catalysis and appear to require prior protonation (at carbonyl) of triplet benzophenone: (*i*) photochemical deuterium exchange of the meta-substituted methyl group of 3-methylbenzophenone and 3-methylacetophenone (12) in deuterated aqueous acid and (*ii*) formal intramolecular redox reaction of some 3-(hydroxymethyl)benzophenones (13) (e.g., eq. [3] with the parent 3-(hydroxymethyl)benzophenone (**5**)). Notably, all the para isomers studied in these reactions were unreactive; the ortho isomers were not studied because of complications that would arise from the known competing intramolecular hydrogen abstraction pathway.

[3] 

In our view, the intramolecular photoredox chemistry of benzophenones deserves further study. Under appropriate dilution and at pH < 3, the reaction was found to be clean with very high quantum yield (eq. [3], $\Phi = 0.6$ at pH 2) (13). The reaction is mediated by water and acid and is unimolecular in substrate: the reaction becomes cleaner on dilution. At high substrate concentrations ($>10^{-5}$ mol/L), bimolecular (via bimolecular hydrogen abstraction, carbonyl abstracting the benzylic hydrogens of the benzyl alcohol) reactions compete giving rise to oligomeric and polymeric products. Photoproduct **6** does not itself undergo a photoredox reaction to give **5**, indicating that not all aromatic carbonyl chromophores can mediate the chemistry and that the question of photoredox reversibility would be an interesting issue to address in other compounds. Moreover, the reaction itself may be viewed as a formal transfer of electrons through the meta positions of the benzene ring, which cannot be accomplished in the ground state. In this paper we report the details of a study that addresses two aspects: (*i*) the structural and electronic effects on the photoredox reaction as ascertained by placing a phenyl and substituted phenyl groups at the benzyl alcohol carbon of **5** (i.e., α-hydroxy-3-benzylbenzophenones **7**–**10**) and (*ii*) the possibility that the photoredox reaction can be induced twice (one after another) in the same substrate on extended photolysis, by studying model compound **11**.

Results and discussion

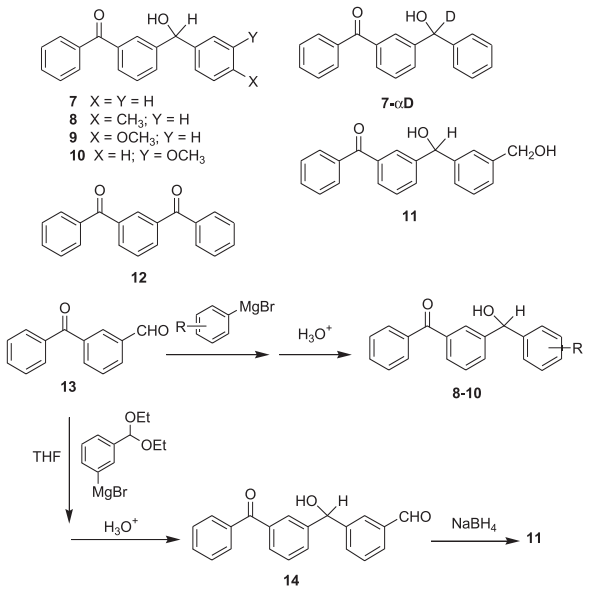
Materials

Whereas α-hydroxybenzylbenzophenones **7** and **7-αD** were readily synthesized by $NaBH_4$ ($NaBD_4$) reduction of commercially available 3-benzoylbenzophenone (**12**), **8**–**11** were synthesized according to the reactions outlined in Scheme 1, all starting from 3-formylbenzophenone (**13**). Compounds **8**–**10** were made by the reaction of **13** with the appropriate Grignard reagent with isolated yields in the 14%–80% range. The synthesis of **11** required the intermediate aldehyde **14**, which was readily made by the reaction of **13** with the Grignard reagent derived from commercially available 3-bromobenzaldehyde diethyl acetal (Sigma-Aldrich). This step proceeded in about 20% isolated yield. The subsequent $NaBH_4$ reduction gave the desired benzophenone diol **11** in 50%.

UV–vis and product studies

In view of the previous finding for the photoredox chemistry of **5** (13) in which higher substrate concentrations increased the proportion of side products because of a bimolecular hydrogen abstraction pathway, photolysis runs were carried out at the most dilute substrate concentrations deemed practical for NMR analysis. Most runs were carried out at 10^{-4} mol/L (10 mg in 400 mL, 1:1 H_2O–CH_3CN, pH 7 and 2, Rayonet RPR 100 reactor, 300 nm lamps, argon

Scheme 1.



purged), and some selected runs were carried out 10^{-5} mol/L (2 mg in 600 mL). Product studies were initially carried out with compounds **7** and **7-αD**. The anticipated photoredox chemistry for these compounds (in aqueous acid solution) would give no observable changes in their UV–vis as the reaction would only interchange the benzophenone ketone and benzhydrol alcohol moieties (with no overall change in molecular structure). To follow the reaction, photolyses of **7** (**7-αD**) were carried out in acidic D_2O (H_2O) and after work-up, NMR spectra were recorded. Photolysis (10^{-4} mol/L) of **7-αD** in 1:1 H_2O–CH_3CN (pH 2, argon purged) resulted in formation of the methine peak at δ 5.9 as would be expected on formation of **7** (≅20% yield) (eq. [4]). The reaction shown interconverts the ketone and alcohol carbons. Although this was not proven in the case of **7** (or **7-αD**), the same reaction for the phenyl-substituted compounds **8** and **10** (vide infra) conclusively shows that the reaction does interchange the carbons concerned. Accompanying the reaction was the formation of broad aromatic signals in the δ 7–7.3 region, indicative of oligomeric material resulting from photoreduction of the benzophenone moiety (Fig. 1) and a trace of the simple photooxidation product **12** (this is the major product when photolyzed with an oxygen or air purge). This oligomeric material proved to be intractable and appears to be a mixture of products. Photolysis at 10^{-5} mol/L gave a cleaner product mixture although the broad peaks observed at δ 7–7.3 could not be completely eliminated. In comparison, the photoredox reaction of **5** under these conditions (i.e., at 10^{-5} mol/L or lower) were exceptionally clean (13). As expected, photolysis of **7** in D_2O–CH_3CN (pD 2) (after H_2O wash before NMR analysis) showed the loss of the methine peak at δ 5.9 with essentially no change in the aromatic region except for growth of broad δ 7–7.3 region due to the formation of oligomers. Thus, **7**

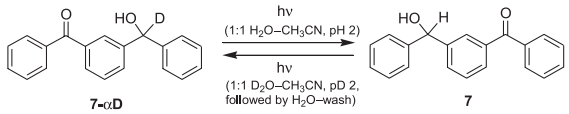
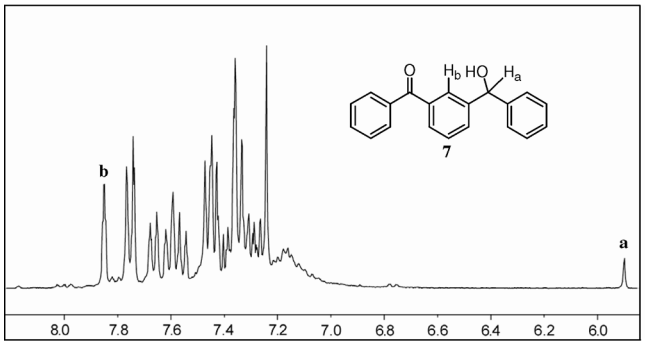
[4] 

Fig. 1. Product mixture observed after photolysis of **7-αD** (10^{-4} mol/L) in 1:1 H_2O–CH_3CN (pH 2) for 2 min at 300 nm. Formation of **7** was determined by observation of a methine peak at δ 5.9 (H_a). Relative ratios of **7** and **7-αD** were calculated by using the H_b proton at δ 7.85 common to both compounds.



and **7-αD** are photochemically interconvertible (eq. [4]). Noteworthy was the fact that photolysis of **7** or **7-αD** in neat CH_3CN or in 1:1 H_2O–CH_3CN above pH 3 did not result in the photoredox reaction shown in eq. [4]; only the broad signals in δ 7–7.3 were observed.

The photoredox reaction of **5** was found to be exceptionally efficient with Φ = 0.6 at pH 2 (13). Using the reaction of **5** as a secondary reference, we have estimated a quantum yield of reaction for **7-αD** to be about 0.3 at pH 2, which further confirms the general high reactivity of these compounds in acid.

As will be shown, all of the photoredox reactions for the phenyl-substituted systems studied in this work (**7**–**11**), regardless of their relative efficiency with respect to the photoredox reaction itself, are accompanied by the formation of oligomeric material as already discussed for **7** and **7-αD**. This is in contrast to what was observed for **5** in which the reaction was exceptionally clean at 10^{-5} mol/L. We believe that the competing reaction(s) are bimolecular in nature and probably involve the triplet benzophenone-like ketone abstracting hydrogen from the benzylic hydrogens of another substrate. In the case of the phenyl-substituted compounds **7**–**11**, the hydrogen to be abstracted is of the benzhydrol type and hence even *more* prone to this reaction. A possible reaction sequence initiated by intermolecular hydrogen abstraction is shown in eq. [5]. Note that in this mechanism one would anticipate a mixture of products in which the benzophenone moiety would suffer "reduction", consistent with the observed NMR (aromatic signals only in the δ 7–7.3 region). This offers a reasonable explanation for the observed concentration-dependent formation of oligomeric products for all of these compounds.

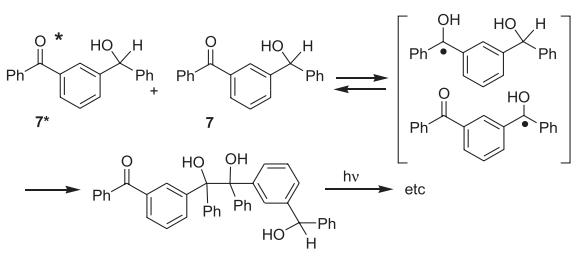
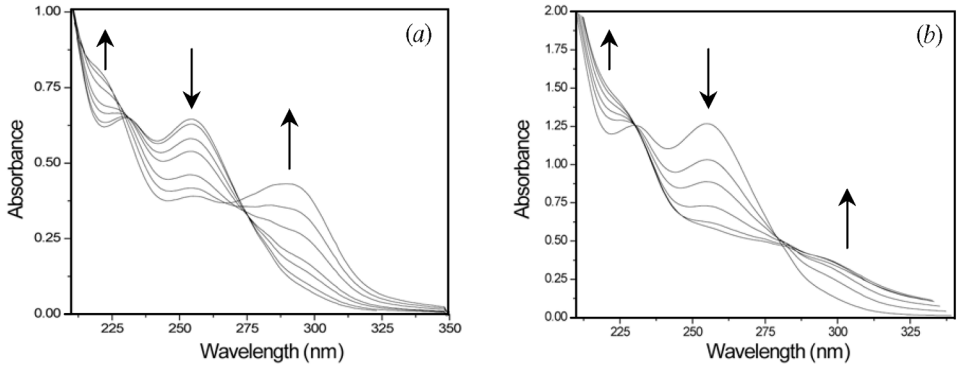
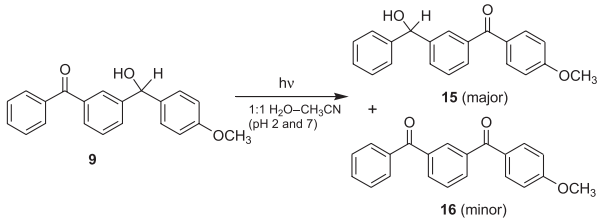
[5] 

Fig. 2. UV–vis traces observed on the photolysis of **9** in 1:1 H_2O–CH_3CN at (*a*) pH 2 and (*b*) pH 7, purged with N_2, at 300 nm. Traces were taken after initial irradiation of 1 min followed by increasing photolysis times of up to 20 min.



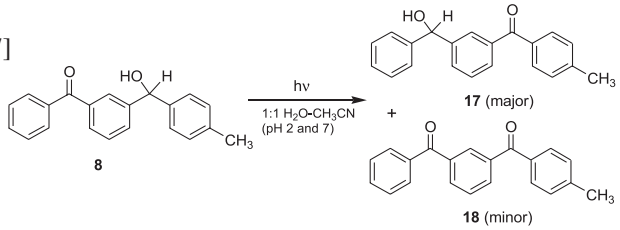
The anticipated photoredox reactions for the methoxy-substituted derivatives **9** and **10** were studied next since reaction would result in significant UV–vis changes. Photolysis of the meta-isomer **10** (pH 2 and 7) resulted in only the loss of substrate and the formation of oligmeric material as noted above for **7**, with no evidence of photoredox reaction. On the other hand, photolysis of the para-isomer **9** resulted in the expected photoredox reaction (eq. [6]) giving **15** (major) and **16** (minor). Notably, at 10^{-5} mol/L substrate, the reaction was much cleaner than **7**, with reaction being observed at pH 7 ($\Phi \cong 0.007$) *and* pH 2 ($\Phi \cong 0.02$), although the quantum yields are both much lower than for **5** and **7**. UV–vis traces carried out for **9** were informative (Fig. 2): photolysis in pH 2 resulted in the formation of a band at 290 nm that is assignable to the expected photoredox product **15**; at pH 7 a much lower yield of this product was observed. Both spectral traces show competing decomposition of the substrate, which is more pronounced at pH 7. Interestingly, **15** was found to be photoinert; that is, the photoredox reaction for **9** (eq. [6]) is not photoreversible. A possible reason for this is provided later.

[6]



The last compound studied in this series was the *p*-methyl-substituted derivative **8**. The intramolecular photoredox reaction was observed at pH 2 (eq. [7]), but it was observed that this compound gave the highest proportion of oligomeric products compared with the other reactive systems discussed so far. Even at 10^{-5} mol/L, low conversion runs gave 10%–20% of the oligomeric products (estimated by comparing the intensity of the signal corresponding to the entire methyl proton region at δ 2.2–2.6 and the sum of the intensities at δ 2.31 and 2.42 corresponding to **8** and **17**, respectively). This is consistent with the greater availability of abstractable benzylic hydrogens (total of 4) in this molecule and the earlier proposal (eq. [5]) that the main competing reaction is due to bimolecular hydrogen abstraction by the benzophenone ketone of another substrate. To further test this assertion, we have carried out the photolysis of **8** in the presence of added naphthalene (a known efficient triplet quencher of benzophenone (1)) at pH 2. The presence of 10^{-4} mol/L naphthalene resulted in a much less efficient reaction and longer photolysis times (up to ten fold) were required, consistent with triplet state reactivity of the benzophenone chromophore of **8**. However, the photoredox reaction was much cleaner and could be taken to almost completion with formation of up to 20%–30% oliogomeric materials as estimated by NMR. This was a significant improvement over runs without added naphthalene. The results are consistent with a photoredox reaction that is unimolecular in substrate (although requiring water and acid mediation) and a competing reaction that is bimolecular in substrate. The addition of naphthalene reduces the lifetime of the reactive triplet state and hence all photochemical pathways. Noteworthy is the finding that in this case, the proportion of bimolecular pathway is retarded more than the unimolecular photoredox pathway, although we do not completely understand why this is so.

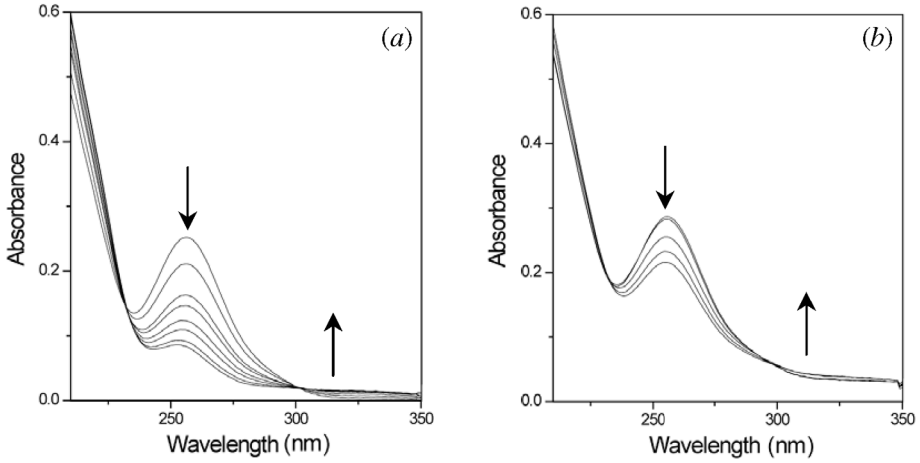
[7]



The photoredox product **17** could not be completely separated from substrate **8** using chromatography. The best that could be achieved was a mixture consisting of 92% **17** and 8% **8** from photolysis in the presence of added naphthalene. Subsequent photolysis of this mixture at pH 2 (300 nm) resulted in no observable change in the ratio of these compounds. Although in principle **17** could undergo the photoredox reaction returning to **8**, this result suggests that the return is very inefficient, and that at this photolysis wavelength the photostationary state has already been attained.

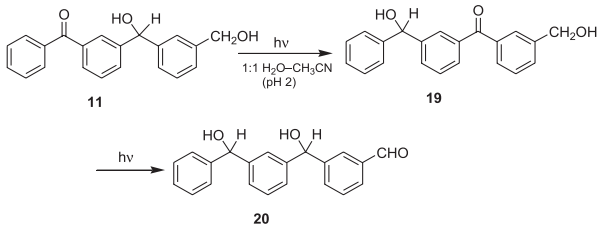
Compound **11** was designed with two oxidizable benzylic alcohol moieties. The idea was that this compound might undergo two photoredox reactions in succession, first forming **19** and then **20** as shown in eq. [8]. Initial studies by UV–vis (Fig. 3) spectra show that photolysis of **11** in acid

Fig. 3. UV–vis traces of the photolysis of **11** in 1:1 H_2O–CH_3CN at 300 nm at (*a*) pH 2 and (*b*) pH 7, purged with N_2. Traces were taken after 1 min of photolysis in each run, with latter runs requiring 2 min photolysis to produce noticeable spectral change.

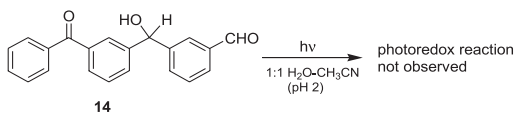


(pH 2) resulted in significantly greater loss of the benzophenone chromphore absorption vs. runs in pH 7, consistent with the acid-catalyzed photoredox reaction. Since **11** and **19** have essentially the same benzophenone chromophore, it was not possible to follow their interconversion using UV–vis. The UV–vis traces are consistent with the eventual formation of **20**, which lacks the benzophenone moiety. Photolysis of **11** at pH 7 gave **14** (up to 10% yield) and oligomeric material. Compound **14** was also observed in all runs carried out in acid (pH 2). Its observation at pH 7 suggests that it is formed via some residual oxidation pathway because of traces of oxygen in the irradiated solution. Interestingly, **14** was found to be photoinert with respect to the photoredox reaction (eq. [9]), as was also the case for the m-methoxyphenyl derivative **10** (vide supra). In addition to **14**, photolysis of **11** in acid (pH 2) did give *both* **19** and **20** shown in eq. [8], although the yield of **20** was always higher than **19** even at the lowest conversions that we were able to conveniently carry out. Thus **19** could not be isolated in pure form and its presence was indicated by NMR assignment of product mixtures that were enriched in **19** by chromatography. It is clear that the reaction scheme shown in eq. [8] can be achieved, in that the end product is formed. Our data suggests that **19** is more reactive than **11** and preferentially undergoes a photoredox reaction to give **20**, although additional studies are warranted to show this in a direct way.

[8]



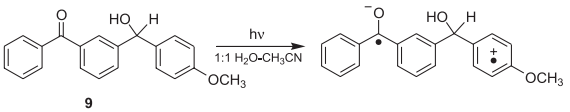
[9]



Nanosecond laser flash photolysis (LFP) studies

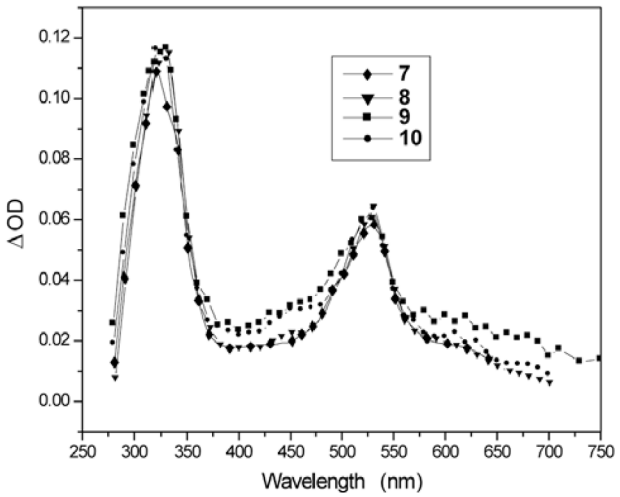
LFP studies were carried out using a Nd-Yag laser at 266 nm (pulse width ≅ 20 ns). Based on our initial LFP studies of the photoredox chemistry of **5** (13), transients assignable to reactive intermediates other than the reactive triplet state were not anticipated. Indeed, LFP of **7** and **8** gave the typical triplet state absorption expected for the benzophenone chromophore with maxima at 325 and 525 nm for **7** and **8** (Fig. 4) (9, 13). However, closer analysis of the spectra observed for both of the methoxyphenyl-substituted compounds **9** and **10** show that in addition to the triplet state signal, bands at ≅450 and >600 nm were also observed superimposed on the triplet signal. Shizuka and co-workers (14) have shown that benzophenone radical anion (450 nm) and methoxybenzene radical cations (630 nm) are produced from electron transfer from methoxybenzenes to triplet excited benzophenone. That the same signals were observed for **9** and **10** under dilute conditions and that the triplet signal itself was the dominant one indicate that intramolecular electron transfer from the methoxybenzene to the triplet excited benzophenone is a competing channel for these two compounds (eq. [10]).

[10]



With respect to the triplet absorption signal itself, the following general findings apply: (*i*) apparent lifetimes were sensitive to oxygen and acid (pH < 3). For **9** the apparent triplet lifetime was 5.2 μs at pH 7 and was reduced to 220 ns at pH 2; for **10** the lifetime was 5.3 μs at pH 7 and 660 ns at pH 2. The addition of oxygen (1 atm; 1 atm = 101.325 kPa) to all samples reduced triplet lifetimes to <100 ns in all cases; (*ii*) most decays could not be fitted to first-order decays and typically required a sum of two first-order decays, especially at pH 7 where there is no quenching of the triplet by acid. This is consistent with competitive pseudo first-order decays (including hydrogen abstraction) pathways. In addition, the benzophenone ketyl absorbs at 545 nm (15) and this overlaps with the 525 nm band of the triplet, mak-

Fig. 4. Triplet absorption spectra of **7**, **8**, **9**, and **10** detected by LFP (Nd-YAG, λ_{ex} = 266 nm) in 1:1 H_2O–CH_3CN (pH 7, N_2 purged) immediately after the laser pulse (≅20 ns).



ing kinetic analysis even more complex. The competition of bimolecular pathways of triplet decay can best be documented for **8** at pH 7 where dilution of the solution induced significantly longer triplet lifetimes: the apparent lifetime at 8.8×10^{-5} mol/L was 2.2 μs whereas at 1.4×10^{-5} mol/L it was 9.1 μs. In view of these complexities, LFP data was used only to infer that the triplet excited state is the reactive state and that it is subject to acid quenching, consistent with photoprotonation at the benzophenone carbonyl (vide supra).

Mechanisms of reaction

As discussed in the Introduction section, the protonation of the oxygen of triplet excited benzophenone in aqueous solution is an important primary photochemical pathway in acid (pH < 3). The more basic carbonyl oxygen in the triplet excited state implies considerable charge transfer from the benzene rings on electronic excitation that is probably enhanced in aqueous solution. Perhaps surprising is the fact that the triplet excited state also retains its ability to abstract hydrogen, as evidenced by the competing hydrogen abstraction pathway observed in this work.

We have carried out simple HOMO and LUMO (Chem 3D, MOPAC/AM1) calculations of the compounds studied in this work to gain possible insights into their relative reactivity. To our pleasant surprise, the experimental observations we have made can be rationalized by the results of these calculations. Shown in Fig. 5 are the calculated HOMOs and LUMOs for the unsubstituted phenyl derivative **7**. The excited state (singlet or triplet) may be viewed in the simplest approximation as attained by promoting an electron from the HOMO to the LUMO. Thus, there would be charge migration from two of the benzene rings (the benzophenone benzene ring with the attached PhCH(OH) group and the benzene ring of the attached Ph(CH)OH itself) to the benzophenone carbonyl and the other benzophenone benzene ring. One would therefore predict the increased basicity of the carbonyl oxygen. Subsequent protonation of the ketone oxygen would give rise to the conjugate acid, which one could argue would retain the electronic distribution of its precursor. A closer examination of Fig. 5 would predict that the benzene ring carbon bearing the PhCH(OH) substituent would be expected to bear most of positive charge in the (redistributed) electronic structure of the excited state (compared with the initial ground state). This is shown in Scheme 2 in which protonation of triplet **7** would give rise to a conjugate acid (carbocation) that may be represented by structures **21a** and **21b**. These predictions are also consistent with the mechanism of photohydration of benzophenone reported by Wirz and co-workers (9). In the case of the photohydration reaction (9), water would attack the carbocation of structure **21b**. This may indeed occur, leading to a product that would eventually return to substrate. However, another possible pathway that is not available in the parent benzophenone studied by Wirz and co-workers (9) is the deprotonation pathway leading to the double enol intermediate **22**. This is perhaps a pathway that initially seems unusual, but one can quickly see that ketonization of this double enol leads back to substrate or to a formal intramolecular redox product that was indeed observed for most of these compounds. Oxygen is expected to trap biradicals of the type **22** leading to the oxidized product **12**, although other mechanisms for photooxidation (photooxygenation) are not excluded.

HOMO and LUMO calculations for the *p*-methylphenyl derivative **8** gave similar results. However, this was not the case for the methoxy-substituted derivatives **9** and **10**. As shown in Fig. 6 for compound **9**, examination of the HOMO and LUMO characteristics would imply that electronic excitation of this compound would transfer charge from only the methoxybenzene ring to *both* of the benzene rings of the benzophenone. This is consistent with the photoinduced single electron transfer to form the benzophenone radical anion and methoxyphenyl radical cation that was inferred in the LFP results for this compound (and **10**). A residual formal photoredox pathway was observed for this compound at pH 7 and pH 2. Indeed, initial photoinduced electron transfer can lead to such a reaction (Scheme 3), and we believe that it is the pathway taken at pH 7. At lower pH, one would still expect protonation of the benzophenone carbonyl, and this may lead to an overall photoredox pathway as well, which is consistent with the higher quantum yield for this reaction at lower pH. The question remains as to why the *m*-methoxy-substituted compound **10** did not undergo photoredox reaction at any pH. Clearly in this case the photoinduced electron transfer appears to take place for **10** as indicated by the LFP data. We believe the explanation lies in the electronic structure of the radical cation shown in Scheme 3. A meta-substituted methoxy group (instead of the para-substituted methoxy group shown) would cause the cation and radical to be more localized at benzene positions that are ortho and para to the methoxy group (for resonance stabilization). This will have the effect of reducing the degree of positive charge that would be localized at the benzene ring carbon adjacent to the Ar(HO)CH moiety. This in term will reduce the acidity of the CH proton of the Ar(HO)CH group and hence the overall efficiency of the formal redox reaction. A similar argument may also be used to explain why photoredox chemistry was not observed when **10** is photoprotonated at pH 2.

Finally, we have also carried out HOMO and LUMO calculations for the photoredox product **15**. As noted earlier, this compound did not undergo the photoredox chemistry

Fig. 5. HOMO (left) and LUMO (right) of **7** calculated using Chem 3D (AMI).

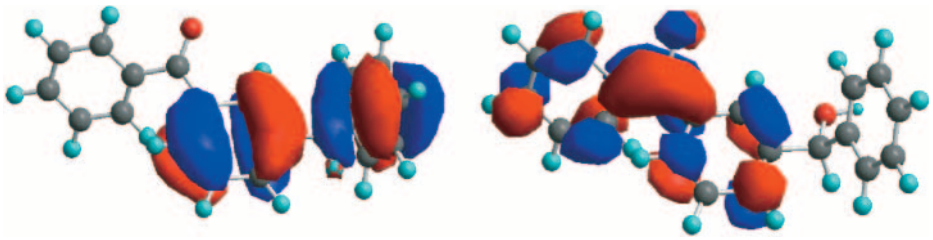
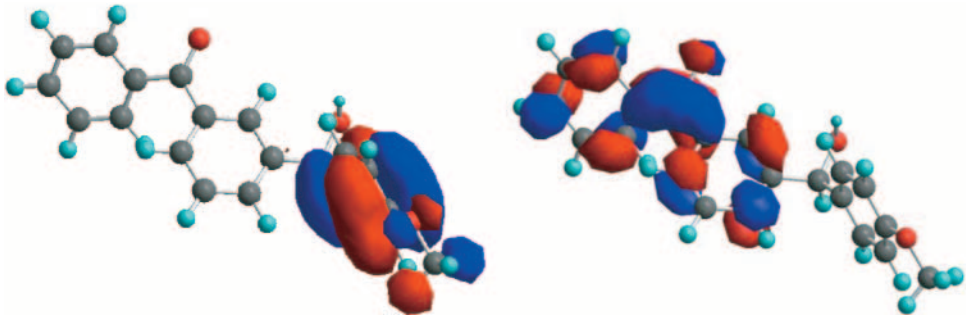
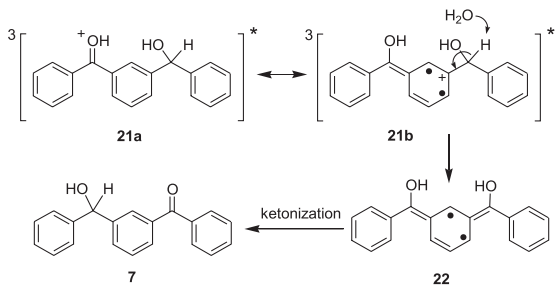


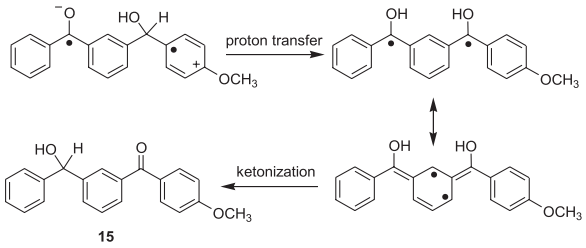
Fig. 6. HOMO (left) and LUMO (right) of **9** calculated using Chem 3D (AM1).



Scheme 2.



Scheme 3.



that would have returned it back to **9**. As shown in Fig. 7, electronic excitation of this compound would result in charge migration from the benzophenone benzene ring substituted with the methoxy group to the carbonyl and the other adjacent benzophenone benzene ring. Although this would make the benzophenone carbonyl more basic (hence photoprotonated by acid), it does not predict that the Ph(HO)CH moiety would be activated with respect to deprotonation, as would be required for the photoredox reaction to proceed and that was predicted in similar HOMO and LUMO calculations for **7** and **8**. Thus, it would appear that simple low level HOMO and LUMO calculations offer a useful parallel study for the intramolecular photoredox chemistry of the benzophenones studied in this work, and we will be applying similar theoretical studies on related chemistry that can arise from acid–base chemistry of electronically excited states of other aromatic compounds.

Experimental section

Instrumentation

^{1}H NMR spectra were recorded on Bruker 300 or 500 MHz instruments. Mass spectra were obtained on a Kratos Concept H instrument. UV–vis spectra were recorded on a Varian Cary 5 instrument. Preparative photolyses were performed using a Rayonet RPR 100 photochemical reactor equipped with 300 nm lamps.

Common laboratory reagents

All solvents used for synthesis (ACS grade) were purchased from Sigma-Aldrich and used as received unless otherwise noted. HPLC grade acetonitrile and distilled water were used in photolyses in mixed H_2O–CH_3CN solutions. D_2O and $CDCl_3$ were purchased from Cambridge Isotope laboratory and D_2SO_4 was obtained from Sigma-Aldrich. Preparative TLC was carried out on 20 cm × 20 cm silica gel GF Uniplates (Analtech).

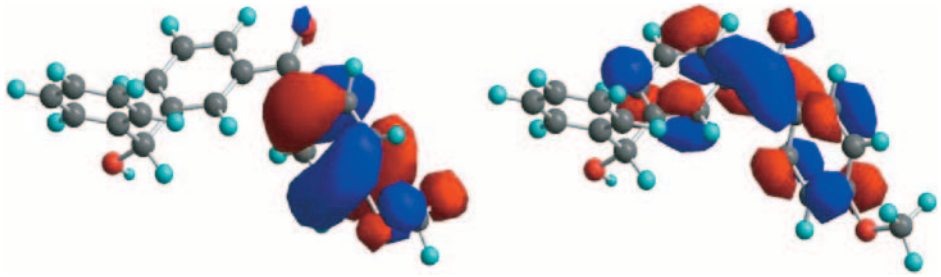
Materials

All readily available organic and inorganic reagents required in the synthesis reported below were purchased from Sigma-Aldrich and used as received.

α-*D*-α-Hydroxy-3-benzylbenzophenone (7-αD)

3-Benzoylbenzophenone (0.30 g, 1.1 mmol) was dissolved in 60 mL of 2-propanol and sodium borodeuteride (0.024 g, 0.56 mmol) in 25 mL of 2-propanol was added slowly with stirring at room temperature (RT). The solution was then refluxed for 45 min, cooled and quenched with 100 mL of

Fig. 7. HOMO (left) and LUMO (right) of **15** calculated using Chem 3D(AM1).



H_2O. Upon extraction with 100 mL of CH_2Cl_2 and removal of the organic solvent, a yellow oil was obtained. Pure **7-αD** was obtained via preparative TLC using 1:24 ether–CH_2Cl_2 to give 0.25 g (oil 50%) of material. ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.84 (t, 2H, 1.8 Hz), 7.74 (dd, 2H, 8.2 Hz and 1.4 Hz), 7.65 (dt, 1H, 7.6 Hz and 1.5 Hz), 7.60 (dt, 1H, 7.7 Hz and 1.6 Hz), 7.56 (tt, 1H, 7.5 and 1.3 Hz), 7.46–7.40 (m, 3H), 7.37–7.35 (m, 2H), 7.34–7.31 (m, 2H), 7.28–7.24 (m, 1H). ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 196.9 (s), 144.4 (s), 143.6 (s), 137.8 (s), 137.6 (s), 132.7 (s), 130.6 (s), 130.3 (s), 129.5 (s), 128.8 (s), 128.6 (s), 128.4 (s), 128.2 (s), 128.0 (s), 126.7 (s). EIMS *m/z*: 289 (M^+, 40), 273 (40), 209 (80), 196 (35), 184 (100), 166 (40), 152 (20). HRMS calcd. for $C_{20}H_{15}DO_2$: 289.1212; found 289.1206.

α-Hydroxy-3-benzylbenzophenone (7)

This compound was prepared the same as the preceding except that sodium borohydride was used. ^{1}H NMR (500 MHz, $CDCl_3$) δ: 7.84 (t, 2H, 1.8 Hz), 7.74 (dd, 2H, 8.2 Hz and 1.4 Hz), 7.65 (dt, 1H, 7.6 Hz and 1.5 Hz), 7.60 (dt, 1H, 7.7 Hz and 1.6 Hz), 7.56 (tt, 1H, 7.5 and 1.3 Hz), 7.46–7.40 (m, 3H), 7.37–7.35 (m, 2H), 7.34–7.31 (m, 2H), 7.28–7.24 (m, 1H). 5.90 (s, 1H), OH signal too broad for detection. ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 196.8 (s), 144.4 (s), 143.7 (s), 137.9 (s), 137.7 (s), 132.7 (s), 130.7 (s), 130.3 (s), 129.5 (s), 128.9 (s), 128.7 (s), 128.5 (s), 128.3 (s), 128.1 (s), 126.8 (s). EIMS *m/z:* 288 (M^+, 15), 272 (10), 209 (30), 195 (10), 183 (50), 105 (100), 77 (60). HRMS calcd. for $C_{20}H_{16}O_2$: 288.1150; found 288.1152.

3-Formylbenzophenone

3-Methylbenzophenone (9.1 mL, 51 mmol) was combined with 2.5 equiv. of *N*-bromosuccinimide (22.8 g, 128 mmol) and benzoyl peroxide (0.11 g, 0.80 mmol) in 100 mL benzene. The reaction mixture was refluxed overnight for 17 h under N_2. After the mixture cooled, it was washed twice with 50 mL of distilled H_2O, dried with anhydr. $MgSO_4$, filtered, and the solvent removed in vacuo. The crude 3-(dibromomethyl)benzophenone was then combined with 5 equiv. of $CaCO_3$ (25.8 g, 258 mmol) in 300 mL 1:1 H_2O–dioxane and refluxed overnight for 17 h. After the reaction mixture had cooled, the solvent was removed under vacuum. Subsequently, 200 mL of CH_2Cl_2 and ~400 mL of 1 mol/L HCl was added with stirring to dissolve the solid. The organic phase was separated and the aqueous phase extracted twice with 100 mL of CH_2Cl_2. The organic fractions were combined and washed twice with 200 mL satd. $NaHCO_3$. The organic fraction was dried with anhydr. $MgSO_4$, filtered, and the solvent removed. Pure white crystals were obtained after chromatography (silica gel, 1:1 ether–hexanes), to yield 2 g (35%) of 3-formylbenzophenone (16). ^{1}H NMR (300MHz, $CDCl_3$) δ: 10.08 (s, 1H), 8.27 (s, 1H), 8.12–8.05 (m, 2H), 7.82–7.78 (m, 2H), 7.69–7.58 (m, 2H), 7.53–7.48 (m, 2H). This material was used without further treatment in the synthesis of **8–10** and **14**.

General procedure for the preparation of benzophenone derivatives 8–10 and 14

For the preparation of the Grignard reagents, 1.2 equiv. of magnesium turnings were reacted with 1.1 equiv. of the corresponding bromobenzene derivative dissolved in dry THF. The Grignard reagents were prepared in the following way. Magnesium turnings and ≅10 mL of dry THF were placed in a dry three-necked flask equipped with a nitrogen inlet, a dropping funnel, and a condenser. The corresponding bromobenzene derivative was dissolved in dry THF and placed in the dropping funnel. Several drops were added to the flask from the dropping funnel. The reaction was initiated by the addition of a crystal of iodine followed by heating. After initiation of the reaction, the remaining solution in the dropping funnel was added slowly to the reaction mixture over 45 min, while the reaction mixture was maintained at ≅40 °C. After the addition was completed, the reaction mixture was heated at reflux for one additional hour. The reaction was cooled to RT and cannulated to the dropping funnel for the next step. In the next reaction, a dry three-necked flask was equipped with a nitrogen inlet, a septum, and a dropping funnel. In this flask was placed a solution of 1 equiv. of 3-formylbenzophenone dissolved in THF. The solution was cooled to –78 °C. The prepared Grignard reagent was added slowly over the period of 2 h to the cooled solution, taking care that the temperature of the reaction mixture remained at –78 °C. After the addition of the reagent, the mixture was stirred for an additional 2 h at –78 °C and allowed to slowly reach RT overnight. The next day water was added to the reaction mixture followed by the addition of 1 mol/L HCl. The reaction mixture was extracted twice with diethyl ether, the organic fraction washed with water and dried over anhydr. $MgSO_4$. The solvent was then evaporated and the residue purified on a column of silica gel using CH_2Cl_2 as the initial eluent followed with CH_2Cl_2–EtOAc mixtures of increasing polarity (up to 20% of EtOAc).

α-*Hydroxy-3-(4′-methylbenzyl)benzophenone (8)*

Starting from 1.2 g (5.7 mmol) of 3-formylbenzophenone and 4-bromotoluene, the reaction furnished 400 mg (23%) of the product, a colorless oil. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 3434, 1656. ^{1}H NMR ($CDCl_3$,

300 MHz) δ: 7.83 (s, 1H), 7.74 (d, 2H, *J* = 7.4 Hz), 7.64 (d, 1H, *J* = 7.4 Hz), 7.52–7.61 (m, 2H,), 7.43 (dd, 2H, *J* = 7.4 Hz, *J* = 7.7 Hz), 7.39 (t, 1H, *J* = 7.7 Hz), 7.23 (d, 2H, *J* = 8.0 Hz), 7.12 (d, 2H, *J* = 8.0 Hz), 5.82 (s, 1H), 2.65 (br s, 1H), 2.31 (s, 3H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 196.9 (s), 144.6 (s), 140.8 (s), 137.7 (s), 137.7 (s), 137.6 (s), 132.6 (d), 130.6 (d), 130.2 (d), 129.5 (d), 129.3 (d), 128.5 (d), 128.4 (d), 128.1 (d), 126.7 (d), 75.8 (d), 21.3 (q). EIMS *m/z*: 303 (M^+, 10), 302 (M^+, 45), 287 (20), 209 (30), 183 (50), 119 (50), 105 (100), 91 (30), 77 (70). HRMS calcd. for $C_{21}H_{18}O_2$: 302.1307; found 302.1306.

α-Hydroxy-3-(4′-methoxybenzyl)benzophenone (9)

Starting from 2.1 g (10 mmol) of 3-formylbenzophenone and 4-bromoanisole, the reaction furnished 460 mg (14%) of the product, a colorless oil. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 3446, 1653. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 7.82 (s, 1H), 7.74 (d, 2H, *J* = 7.5 Hz), 7.64 (dd, 1H, *J* = 1.4 Hz, *J* = 7.4 Hz), 7.52–7.61 (m, 2H), 7.44 (dd, 2H, *J* = 7.5 Hz, *J* = 8.1 Hz), 7.41 (t, 1H, *J* = 8.1 Hz), 7.22 (d, 2H, *J* = 8.8 Hz), 6.84 (d, 2H, *J* = 8.8 Hz), 5.83 (s, 1H), 3.76 (s, 3H), 2.50 (br s, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 196.9 (s), 159.4 (s), 144.6 (s), 137.8 (s), 137.7 (s), 136.0 (s), 132.7 (d), 130.5 (d), 130.3 (d), 129.4 (d), 128.5 (d), 128.5 (d), 128.1 (d), 128.1 (d), 114.2 (d), 75.6 (d), 55.5 (q). EIMS *m/z*: 319 (M^+, 10), 318 (M^+, 60), 182 (40), 137 (50), 105 (100), 86 (75), 77 (88), 69 (100). HRMS calcd. for $C_{21}H_{18}O_3$: 318.1256; found 318.1255.

α-Hydroxy-3-(3′-methoxybenzyl)benzophenone (10)

Starting from 2.65 g (12.6 mmol) of 3-formylbenzophenone and 3-bromoaniosle, the reaction furnished 3.2 g (80%) of the product, a colorless oil. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 3435, 1656. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 7.83 (s, 1H), 7.74 (d, 2H, *J* = 8.1 Hz), 7.64 (d, 1H, *J* = 7.4 Hz), 7.52–7.61 (m, 2H), 7.43 (dd, 2H, *J* = 7.7 Hz, *J* = 8.1 Hz), 7.41 (t, 1H, *J* = 7.7 Hz), 7.23 (dd, 1H, *J* = 8.1 Hz, *J* = 8.3 Hz), 6.90–6.95 (m, 2H), 6.78 (d, 1H, J = 8.3 Hz), 5.83 (s, 1H), 3.76 (s, 3H), 2.50 (br s, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 196.8 (s), 160.0 (s), 145.3 (s), 144.3 (s), 137.8 (s), 137.6 (s), 132.7 (d), 130.6 (d), 130.3 (d), 129.9 (d), 129.5 (d), 128.6 (d), 128.5 (d), 128.2 (d), 119.0 (d), 113.4 (d), 112.3 (d), 75.9 (d), 55.4 (q). EIMS *m/z*: 319 (M^+, 25), 318 (M^+, 100), 209 (25), 183 (40), 109 (55), 105 (78), 77 (60). HRMS calcd. for $C_{21}H_{18}O_3$: 318.1256; found 318.1254.

α-Hydroxy-3-(3′-formylbenzyl)benzophenone (14)

Starting from 2.0 g (9.5 mmol) of 3-formylbenzophenone, 255 mg of Mg (10.5 mmol), and 2.71 g of 3-bromobenzaldehyde diethyl acetal (10.5 mmol) (Sigma-Aldrich), the reaction furnished 560 mg (19%) of the product, a colorless oil. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 3434, 1695, 1653. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 9.98 (s, 1H), 7.91 (s, 1H), 7.84 (s, 1H), 7.78 (d, 1H, *J* = 7.8 Hz), 7.74 (d, 2H, *J* = 8.1 Hz), 7.63–7.70 (m, 2H), 7.53–7.62 (m, 2H), 7.50 (t, 1H, *J* = 7.6 Hz), 7.44 (dd, 1H, *J* = 7.6 Hz, *J* = 8.1 Hz), 7.40–7.48 (m, 1H), 5.98 (s, 1H), 2.10 (br s, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 196.7 (s), 192.4 (d), 144.8 (s), 143.9 (s), 138.2 (s), 137.5 (s), 136.9 (s), 132.8 (d), 132.7 (d), 130.7 (d), 130.3 (d), 129.9 (d), 129.6 (d), 129.4 (d), 128.9 (d), 128.5 (d), 128.2 (d), 127.7 (d), 75.5 (d). EIMS *m/z*: 317 (M^+, 5), 316 (M^+, 20), 270 (25), 239 (30), 212 (25), 183 (70), 165 (15), 135 (20), 122 (20), 105 (100), 77 (85). HRMS calcd. for $C_{21}H_{16}O_3$: 316.1099; found 316.1097.

α-Hydroxy-3-[3′-(hydroxymethyl)benzyl]benzophenone (11)

The aldehyde **14** (450 mg, 1.4 mmol) was dissolved in 30 mL of MeOH and cooled under ice. To this solution was added a solution of $NaBH_4$ (40 mg, 1 mmol) in 10 mL of MeOH. The reaction mixture was stirred at 0 °C for 15 min and quenched by the addition of 50 mL of saturated ammonium chloride. Extractions with CH_2Cl_2 were carried out and the collected extracts were dried over anhydr. $MgSO_4$. After evaporation of the solvent, the residue was chromatographed on silica using CH_2Cl_2 as the initial eluent followed with CH_2Cl_2–EtOAc mixtures of increasing polarity (up to 30% of EtOAc). The product was obtained as a colorless oil, 215 mg, yield 48%. IR (neat, NaCl plates, cm^{-1}) ν: 3390, 1651. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 7.85 (s, 1H), 7.75 (d, 2H, *J* = 7.4 Hz), 7.66 (d, 1H, *J* = 7.8 Hz), 7.53–7.63 (m, 2H), 7.45 (dd, 1H, *J* = 7.4 Hz, *J* = 7.6 Hz), 7.43 (t, 1H, *J* = 7.6 Hz), 7.39 (s, 1H), 7.25–7.35 (m, 3H), 5.91 (s, 1H), 4.67 (s, 2H), 2.57 (br s, 2H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 197.0 (s), 144.4 (s), 144.0 (s), 141.6 (s), 137.8 (s), 137.6 (s), 132.8 (d), 130.7 (d), 130.3 (d), 129.5 (d), 129.0 (d), 128.6 (d), 128.5 (d), 128.2 (d), 126.6 (d), 126.0 (d), 125.2 (d), 75.9 (d), 65.2 (t). EIMS *m/z*: 319 (M^+, 5), 318 (M^+, 20), 209 (38), 183 (35), 135 (28), 105 (100), 77 (50). HRMS calcd. for $C_{21}H_{18}O_3$: 318.1256; found 318.1254.

General photolysis procedure

A 10 mg sample of the benzophenone derivative was dissolved in 400 mL of 1:1 CH_3CN–H_2O and placed in a 600 mL quartz tube, which was continuously cooled with a cold finger to ~15 °C. The pH of the water portion was adjusted by the addition of H_2SO_4. The solution was purged with argon and irradiated at 300 nm in a Rayonet RPR 100 photochemical reactor using 2 or 16 lamps for different times (1–30 min). After irradiation, the solution was neutralized by the addition of $NaHCO_3$ and extracted using CH_2Cl_2. The combined extracts were dried over $MgSO_4$ and the solvent was evaporated. After evaporation of the solvent, photolysis mixtures were analyzed by NMR and (or) chromatographed on a thin layer of silica using CH_2Cl_2–EtOAc as eluent to separate photoproducts.

Photolysis of α-hydroxy-3-(4′-methylbenzyl)benzophenone (8)

A solution of **8** (10 mg in 400 mL, pH 2) was photolyzed (300 nm, 2 lamps) in a quartz tube for up to 20 min. After work-up the residue was chromatographed on prep. TLC to give **18** and a mixture of **8** and **17** (maximum isolated yield of **17** was 20%). The highest content of **17** (92%) was obtained on photolysis in the presence of naphthalene. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 3434, 1652. ^{1}H NMR ($CDCl_3$, 500 MHz) δ: 7.82 (dd, 1H, *J* = 1.7 Hz, *J* = 1.9 Hz), 7.66 (d, 2H, *J* = 8.1 Hz), 7.64 (ddd, 1H, *J* = 1.2 Hz, *J* = 1.6 Hz, *J* = 7.5 Hz), 7.58 (ddd, 1H, *J* = 1.1 Hz, *J* = 1.6 Hz, *J* = 7.7 Hz), 7.41 (t, 1H, *J*= 7.7 Hz), 7.37 (d, 2H, *J* = 8.5 Hz), 7.33 (dd, 2H, *J* = 7.7 Hz, *J* = 8.5 Hz), 7.25–7.28 (m, 1H), 7.24 (d, 2H, *J* = 8.1 Hz), 5.89 (s, 1H), 2.42 (s, 3H),

2.35 (br s, 1H). ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 196.5 (s), 144.3 (s), 143.7 (s), 143.5 (s), 138.3 (s), 135.0 (s), 130.5 (d), 130.4 (d), 129.4 (d), 129.2 (d), 128.9 (d), 128.6 (d), 128.1 (d), 128.1 (d), 126.8 (d), 76.2 (d), 21.9 (q). EIMS *m/z*: 303 (M^+, 10), 302 (M^+, 30), 279 (10), 223 (15), 212 (40), 197 (50), 165 (20), 149 (30), 133 (50), 119 (60), 105 (100), 91 (30), 77 (70). HRMS calcd. for $C_{21}H_{18}O_2$: 302.1307; found 302.1307.

The oxidized product **18** was also isolated from the preparative TLC as a colorless oil. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 1659. ^{1}H NMR ($CDCl_3$, 500 MHz) δ: 8.13 (dd, 1H, *J* = 1.8 Hz, *J* = 1.7 Hz), 7.96–8.00 (m, 2H), 7.79 (dd, 2H, *J* = 1.7 Hz, *J* = 8.0 Hz), 7.70 (d, 2H, *J* = 8.1 Hz), 7.59 (dt, 1H, *J* = 1.7 Hz, *J* = 7.7 Hz), 7.58 (ddd, *J* = 1.5 Hz, *J* = 7.0 Hz, *J* = 7.5 Hz), 7.47 (dd, 2H, *J* = 7.7 Hz, *J* = 8.0 Hz), 7.26 (d, 2H, *J* = 8.1 Hz), 2.41 (s, 3H). ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 196.1 (s), 195.8 (s), 144.0 (s), 138.4 (s), 138.0 (s), 137.3 (s), 134.5 (s), 133.6 (d), 133.5 (d), 133.1 (d), 131.3 (d), 130.5 (d), 130.3 (d), 129.4 (d), 128.7 (d), 21.9 (q). EIMS *m/z*: 301 (M^+, 10), 300 (M^+, 60), 279 (10), 223 (15), 209 (10), 167 (20), 149 (35), 119 (100), 105 (50), 91 (30), 77 (30). HRMS calcd. for $C_{21}H_{16}O_2$: 300.1150; found 300.1152.

Photolysis of 8 in the presence of naphthalene

A 400 mL of the CH_3CN–H_2O solution (pH 2) containing 10 mg of **8** and 50 mg of naphthalene was purged with argon and irradiated for 1 h at 300 nm (16 lamps). After irradiation, extractions with CH_2Cl_2 were carried out. The collected extracts were dried over anhydr. $MgSO_4$ and the solvent evaporated. The residue obtained from 3 photolyses was chromatographed on a prep. TLC (silica gel; CH_2Cl_2–EtOAc (2.5%)). The following fractions were isolated: ~10 mg of **18** and ~ 7 mg of the mixture containing 92% of **17** and 8% of the starting material **8**.

Photolysis of α-hydroxy-3-(4′-methoxybenzyl)benzophenone (9)

A solution of **9** (10 mg in 400 mL, pH 2) was photolyzed (300 nm, 16 lamps) in a quartz tube for up to 10 min. After work-up the residue was chromatographed on prep. TLC to give pure **15** as a colorless oil (maximum isolated yield of **15** was 40%–50%). IR (neat, NaCl plates, cm^{-1}) ν: 3429, 1646. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 7.77 (s, 1H), 7.76 (d, 2H, *J* = 8.8 Hz), 7.60 (d, 1H, *J* = 7.5 Hz), 7.57 (d, 1H, *J* = 8.1 Hz), 7.22–7.44 (m, 6H), 6.92 (d, 2H, *J* = 8.8 Hz), 5.86 (s, 1H), 3.86 (s, 3H), 2.76 (br s, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 195.7 (s), 163.4 (s), 144.3 (s), 143.7 (s), 138.5 (s), 132.8 (d), 130.3 (s), 130.2 (d), 129.1 (d), 128.8 (d), 128.5 (d), 128.0 (d), 126.7 (d), 113.7 (d), 76.1 (d), 55.7 (q). EIMS *m/z*: 319 (M^+, 10), 318 (M^+, 60), 279 (15), 256 (15), 239 (15), 213 (50), 165 (20), 149 (70), 135 (100), 121 (30), 105 (100), 97 (30), 77 (87). HRMS calcd. for $C_{21}H_{18}O_3$: 318.1256; found 318.1257.

The oxidized product **16** was also isolated as a colorless oil. IR (neat from CH_2Cl_2 solution, salt plates, cm^{-1}) ν: 1654. ^{1}H NMR ($CDCl_3$, 300 MHz) δ: 8.10 (s, 1H), 7.97 (d, 1H, *J* = 7.2 Hz), 7.95 (d, 1H, *J* = 7.5 Hz), 7.76–7.84 (m, 4H), 7.54–7.62 (m, 2H), 7.47 (dd, 2H, *J* = 7.0 Hz, *J* = 7.8 Hz), 6.94 (d, 2H, *J* = 8.8 Hz), 3.86 (s, 3H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ: 196.2 (s), 196.1 (s), 163.8 (s), 138.7 (s), 137.9 (s), 137.2 (s), 133.4 (d), 133.2 (d), 133.0 (d), 132.8 (d), 131.1 (d), 130.3 (d), 129.8 (s), 128.7 (d), 114.0 (d), 55.8 (q). EIMS *m/z*: 317 (M^+, 5), 316 (M^+, 20), 279 (30), 212 (25), 167 (40), 149 (100), 135 (95), 105 (30), 77 (35). HRMS calcd. for $C_{21}H_{16}O_3$: 316.1099; found 316.1101.

Photolysis of α-hydroxy-3-[4′-(hydroxymethyl)benzyl]benzophenone (11)

A solution of **11** (10 mg in 400 mL, pH 2) was photolyzed at 300 nm for up to 15 min. After work-up, the residue was separated by prep. TLC. The main product was **20** (maximum isolated yield 5%–10%) as a mixture of diastereomers (colorless oil). IR (neat, NaCl plates, cm^{-1}) ν: 3402, 1694. ^{1}H NMR ($CDCl_3$, 500 MHz) δ: 9.96 (s, 1H), 9.95 (s, 1H), 7.86 (2d, 2H, *J* = 1.8 Hz), 7.76 (2dd, 2H, *J* = 1.4 Hz, *J* = 7.7 Hz), 7.62 (2dd, 2H, *J* = 1.8 Hz, *J* = 7.6 Hz), 7.47 (2dd, 2H, *J* = 7.6 Hz, *J* = 7.7 Hz), 7.42–7.45 (m, 2H), 7.12–7.34 (m, 16H), 5.87 (s, 2H), 5.81 (s, 2H). ^{13}C NMR ($CDCl_3$, 125 MHz) δ: 192.5 (d), 145.0 (s), 144.6 (s), 144.6 (s), 143.8 (s), 143.8 (s), 143.7 (s), 143.7 (s), 136.8 (s), 132.7 (d), 129.4 (d), 129.2 (d), 129.1 (d), 128.8 (d), 128.0 (d), 127.9 (d), 127.9 (d), 127.9 (d), 126.8 (d), 126.8 (d), 126.5 (d), 126.4 (d), 126.1 (d), 126.0 (d), 125.0 (d), 76.4 (d), 76.3 (d), 75.9 (d), 75.9 (d). EIMS *m/z*: 319 (M^+, 7), 318 (M^+, 35), 239 (30), 211 (20), 183 (20), 167 (30), 133 (20), 105 (100), 77 (45). HRMS calcd. for $C_{21}H_{18}O_3$: 318.1256; found 318.1254.

Also found were **14** (identified by comparison to an authentic sample made above) and a trace amount of **19** was detected in the photomixture, which could not be purified. ^{1}H NMR of an enriched TLC fraction assignable to **19** is as follows: ($CDCl_3$, 500 MHz) δ: 7.83 (s, 1H), 7.73 (s, 1H), 7.67 (d, 2H, *J* = 7.4 Hz), 7.62 (d, 1H, *J* = 7.7 Hz), 7.58 (d, 1H, *J* = 7.4 Hz), 7.40–7.48 (m, 2H), 7.24–7.40 (m, 5H), 5.90 (s, 1H), 4.73 (s, 2H).

Nanosecond laser flash photolysis (LFP)

All LFP studies were conducted at the University of Victoria LFP facility employing a Nd-YAG laser with a pulse width of 20 ns and excitation wavelength of 266 nm. Flow cells (0.7 cm) were used and solutions were purged with nitrogen or oxygen for 30 min prior to measurements. Optical densities at 266 nm were ~0.1–0.7.

Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada and the University of Victoria.

References

1. N.J. Turro. Modern molecular photochemistry. University Science Books, Mill Valley, Calif. 1991.
2. W.M. Horspool and P.-S. Song. CRC Handbook of organic photochemistry and photobiology. CRC Press, Boca Raton, Fla. 1995.
3. G. Ciamician and P. Silber. Ber. **33**, 2911 (1900).
4. G.S. Hammond and W.M. Moore. J. Am. Chem. Soc. **81**, 6334 (1959).
5. W.M. Moore, G.S. Hammond, and R.P. Foss. J. Am. Chem. Soc. **83**, 2789 (1962).

6. M.B. Ledger and G. Porter. J. Chem. Soc., Faraday Trans. 1, **68**, 539 (1972).
7. J.F. Ireland and P.A.H. Wyatt. J. Chem. Soc., Faraday Trans. 1, **69**, 161 (1973).
8. D.M. Rayner and P.A.H. Wyatt. J. Chem. Soc., Faraday Trans. 2, **70**, 945 (1974).
9. M. Ramseier, P. Senn, and J. Wirz. J. Phys. Chem. A, **107**, 3305 (2003).
10. H.E. Zimmerman. J. Am. Chem. Soc. **117**, 8988 (1995).
11. H.E. Zimmerman. J. Phys. Chem. A, **102**, 5616 (1998).
12. L.A. Huck and P. Wan. Org. Lett. **6**, 1797 (2004).
13. D. Mitchell, M. Lukeman, D. Lehnherr, and P. Wan. Org. Lett. **7**, 3387 (2005).
14. K. Okada, M. Yamaji, and H. Shizuka. J. Chem. Soc., Faraday Trans. **94**, 861 (1998).
15. K. Takeda, Y. Kajii, K. Shibuya, and K. Obi. J. Photochem. Photobiol. A, **115**, 109 (1998).
16. P. Miziak, J. Zon, N. Amrhein, and R. Gancarz. Phytochemistry, **68**, 407 (2007).