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PHOTOINDUCED REACTIONS—XXIX

THE PHOTOCHEMICAL REACTION OF 3,5-DI-*t*-BUTYL-4-HYDROXYPHENYL KETONES. EVIDENCE FOR THEIR PHOTOTAUTOMERIZATION[1]

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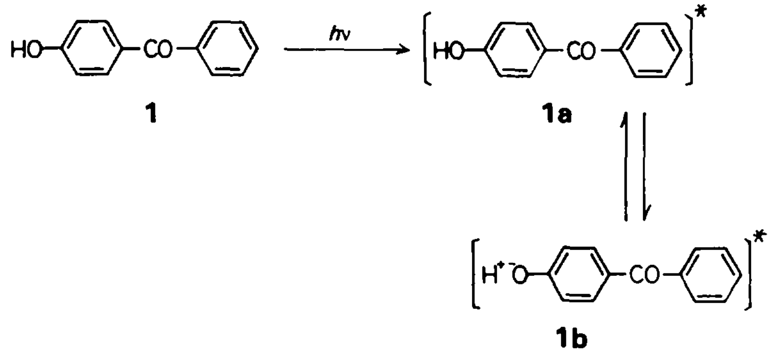
Abstract—In accordance with the result in the photolysis of 4-hydroxybenzophenone, 3,5-di-t-butyl-4-hydroxybenzophenone (**2**) and 3,5-di-t-butyl-4-hydroxyacetophenone (**3**) were found to be photochemically unreactive in isopropyl alcohol. However, irradiation of **2** and **3** in cyclohexane resulted in novel de-t-butylation to give 3-t-butyl-4-hydroxybenzophenone (**7**) and 3-t-butyl-4-hydroxyacetophenone (**10**), respectively. Quenching experiments for the de-t-butylation reaction showed that the reaction occurs *via* triplet excited state. Photooxygenation of **2** and **3** in cyclohexane resulted in oxidative cleavage to give benzoic acid and acetic acid, respectively, in addition to 2,6-di-t-butylbenzoquinone (**13**). In triethylamine **2** and **3** were photoreduced to yield 3,5-di-t-butyl-4-hydroxybenzhydrol (**14**) and the corresponding pinacol **16**, respectively. Mechanisms involving triplet excited state and phototautomerization are discussed. 3,5-Di-t-butyl-2-hydroxybenzophenone (**25**), an analog of **2**, and 2-hydroxy-5-methylbenzophenone were photochemically unreactive under various conditions. 3,5-Di-t-butyl-4-methoxybenzophenone (**5**) was readily photoreduced to give the corresponding pinacol **6**.

RECENT studies concerning the photochemical reactivity of aromatic ketones and of their ring-substituted derivatives have elucidated the effect of substituents on the reactivity and the lowest excited state nature of these compounds.[2] It is now clarified that the photochemical reactivity of aromatic ketones depends on the nature of their lowest triplet state and that the n,π^* triplet is the reactive species.[3,4] The introduction of substituents into the aromatic ring of benzophenone alters drastically the ability for intermolecular H atom abstraction depending on the solvent used. For instance, the quantum yield for disappearance of 4-hydroxybenzophenone (**1**) in isopropyl alcohol is very low (ϕ = 0·02–0·00) while it rises markedly in cyclohexane (ϕ = 0·9) leading to the corresponding pinacol.[5,6] On the other hand, 4-methoxybenzophenone has the lowest n,π^* triplet state in both solvents and therefore is efficiently photoreduced in isopropyl alcohol (ϕ = 1·00) and in cyclohexane (ϕ = 0·5) to give the corresponding pinacol.[5] The failure of 4-hydroxybenzophenone (**1**) to photoreduce in isopropyl alcohol, despite the fact that it also has a lowest n,π^* triplet state is attributed to the much higher pK of the excited state. The excited molecules must react in the unprotonated form **1b** which is produced by proton ejection in the excited state. Apparently, the unprotonated form **1b** is very unreactive toward H atom abstraction because of the strongly electron-donating nature of the phenolate group. The unprotonated form **1b** is not stabilized by a non-polar solvent, cyclohexane, and the equilibrium concentration of the protonated form **1a** in the n,π^* triplet state increases. Thus, **1** is efficiently photoreduced. Analogous studies con-

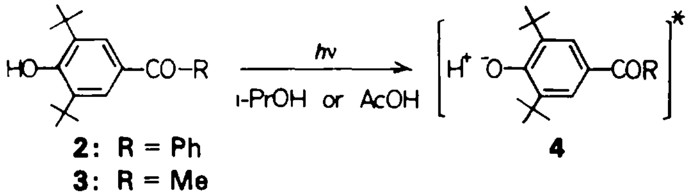


cerning the photochemical reactivity of acetophenone and its ring-substituted derivatives have been also reported.[7,8]

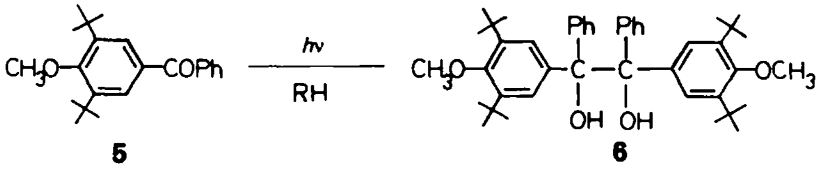
In this paper we report the photochemical reaction of 3,5-di-t-butyl-4-hydroxybenzophenone (**2**) and 3,5-di-t-butyl-4-hydroxyacetophenone (**3**) in various media and the effect of bulky t-butyl substituents at positions 3 and 5 on the photoreactivity of 4-hydroxyphenyl ketones.

RESULTS AND DISCUSSION

Irradiation of **2** *and* **3** *in protic solvents.* On irradiation in isopropyl alcohol, with light filtered through Pyrex 3,5-di-t-butyl-4-hydroxybenzophenone (**2**) and 3,5-di-t-butyl-4-hydroxyacetophenone (**3**) were recovered completely unchanged. The benzophenone **2** was also photochemically unreactive in acetic acid. As in the case of 4-hydroxybenzophenone (**1**), the stability of **2** and **3** can be attributed to predominant formation of unprotonated form **4** of their excited state. Protic solvents such as isopropyl alcohol and acetic acid would stabilize the unprotonated form of the excited state of **2** and **3**.

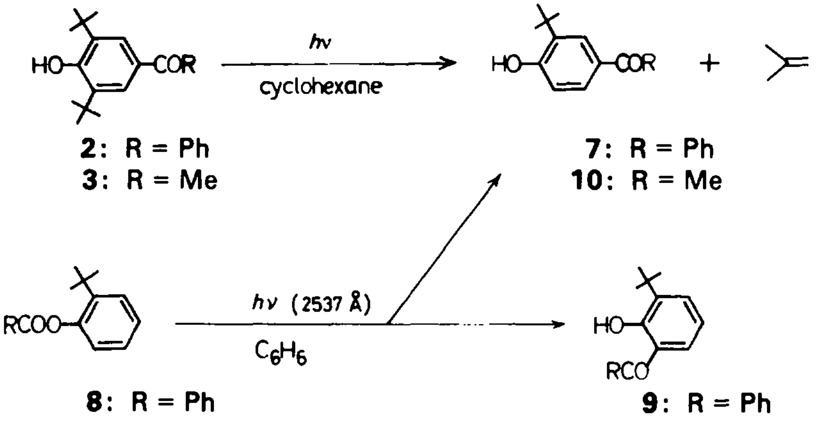


On the other hand, irradiation of 3,5-di-t-butyl-4-methoxybenzophenone (**5**) resulted in the formation of the corresponding pinacol **6** in 55% yield. On irradiation in cyclohexane **5** also gave **6** in 30% yield. The structure of the pinacol was deduced from its spectral properties (Experimental). The result is consistent with the similar photopinacolization of 4-methoxybenzophenone,[6] in which the n,π^* excited triplet is the reactive species.



Photochemical de-t-butylation of **2** *and* **3**. It has been reported that irradiation of 4-hydroxybenzophenone (**1**) in cyclohexane gave the corresponding pinacol as a sole product in high quantum yield.[5,6] In sharp contrast, irradiation of **2** in cyclohexane resulted in de-t-butylation to give isobutylene (23%, isolated as the dibromide) and 3-t-butyl-4-hydroxybenzophenone (**7**, 50%) in addition to a cyclohexane adduct (15·5%), and no pinacol formation was observed. Treatment of **7** with aluminum chloride in benzene gave 4-hydroxybenzophenone (**1**). The structure of **7** was confirmed by its synthesis. Irradiation of 2-t-butylphenyl benzoate (**8**) in benzene with a low-pressure mercury arc lamp according to the procedure of Kobsa,[9] gave **7** in 20% yield together with 3-t-butyl-2-hydroxybenzophenone (**9**) in 35% yield. The mass spectrum of the cyclohexane adduct exhibits the parent peak at *m/e* 392 and the IR spectrum shows a carbonyl band at 1700 cm^{-1} but no hydroxyl band. The structure of the adduct, however, still remains to be elucidated.

Irradiation of 3,5-di-t-butyl-4-hydroxyacetophenone (**3**) in cyclohexane also resulted in de-t-butylation to give 3-t-butyl-4-hydroxyacetophenone (**10**) in 95% yield. In this case the corresponding cyclohexane adduct and pinacol were not detected in the reaction mixture. Treatment of **10** with aluminum chloride in benzene gave 4-hydroxyacetophenone. The structure of **10** was confirmed by its synthesis analogous to that of **7**. Thus, 2-t-butylphenyl acetate (**11**) underwent photo-Fries rearrangement[9] to give **10** and 3-t-butyl-2-hydroxyacetophenone (**12**) in 24 and 26% yield, respectively.



2: R = Ph
3: R = Me

7: R = Ph
10: R = Me

8: R = Ph
11: R = Me

9: R = Ph
12: R = Me

As in the case of 4-hydroxybenzophenone (**1**), 4-hydroxyacetophenone is known to be practically unreactive on photolysis in isopropyl alcohol (ϕ = 0·03).[8] However, in contrast with **1**, 4-hydroxyacetophenone is photochemically much less reactive in cyclohexane and is recovered unchanged.[6,7,10] Considering the low reactivity of 4-hydroxyacetophenone in cyclohexane, it is of interest that the photochemical behaviour of **3** in cyclohexane is quite analogous to that of **2**.†

Quenching experiments. In order to gain information on the multiplicity of excited states responsible for the de-t-butylation of **2** and **3**, quenching experiments using

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† All of the ring-substituted acetophenones investigated have a π, π* triplet as their lowest triplet state, and therefore they should be less reactive.

piperylene, a triplet quencher,† were carried out. A 0·25 × 10^{-3} M solution of **2** or **3** in cyclohexane was irradiated with or without piperylene. The results are summarized in Table 1. In the presence of piperylene (4·0 × 10^{-2} M), the disappearance of **2** was effectively suppressed and that of **3** was completely inhibited. The results indicate that the photochemical de-t-butylation of **2** and **3** occurs *via* their excited triplet states, although the possibility cannot be ruled out that in the case of **2** the singlet state may be partly responsible for the de-t-butylation. Considering the fact that the methyl ether **5** was easily photoreduced in cyclohexane to the pinacol **6**, it is inferred that the 4-hydroxyl group of **2** plays an important role in the photochemical de-t-butylation reaction.

TABLE 1. IRRADIATION OF 2 AND 3 WITH OR WITHOUT PIPERYLENE IN CYCLOHEXANE

Compound (Concn., M)	Piperylene added (Concn., M)	Compound remaining after 10 hr irradiation (%)
2 (0·25 × 10^{-3})	none	11·6
2 (0·25 × 10^{-3})	0·5 × 10^{-2}	57·4
2 (0·25 × 10^{-3})	4·0 × 10^{-2}	80·6
3 (0·25 × 10^{-3})	none	73·6
3 (0·25 × 10^{-3})	0·5 × 10^{-2}	96·0
3 (0·25 × 10^{-3})	4·0 × 10^{-2}	100·0

Experiments with isotopically labeled **2**. It appeared necessary to know the source of the H atom at position 5 of the de-t-butylated products **7** and **10** in order to elucidate the reaction mechanism. Therefore, 3,5-di-t-butyl-4-deuterioxybenzophenone (**2a**) was prepared and photolyzed in cyclohexane under the similar conditions. Deuterated 3-t-butyl-4-hydroxybenzophenone (**7a**) separated directly from the photolyzed mixture, exhibits IR bands at 3330 (OH), 2490 (OD), 992, 897, 856 and 782 cm^{-1}. The latter four bands are assigned to aromatic C–D band. From the NMR peak area of the OH proton signal deuterium enrichment of the phenoxyl group of **7a** was estimated as 47%. Treatment of **7a** with methanol resulted in hydrogen exchange of the O–D group to give **7b** which showed no O–D band in its IR spectrum. Deuterium enrichment of **7b** was estimated as 48% by a mass spectrometric analysis.[12]

The structure of **7b** was confirmed by synthesis. Irradiation of 2-t-butyl-4,6-dideuteriophenyl benzoate (**8a**) (total deuterium enrichment, 70%) in benzene with 2537 Å light followed by treatment of the products with ethanol afforded 3-t-butyl-4-hydroxy-5-deuterioxybenzophenone (**7b**) and 2-hydroxy-3-t-butyl-5-deuterioxybenzophenone (**9b**) in 16 and 30% yield, respectively. The IR spectrum of the former product was superimposable to that of **7b** obtained from **2a**. The deuterium enrichments of **7b** and **9b** obtained by the photo-Fries rearrangement of **8a** were found by mass spectrometric analyses to be 69 and 67%, repsectively.

The labeled experiments suggest that the H atom at position 5 of the de-t-butylated product **7** was derived from the OH group of **2**. The low deuterium content (48%) at position 5 of **7b** can be rationalized by a D–H exchange reaction between the starting material **2a** and the ring-deuterated product **7d** during irradiation, as shown

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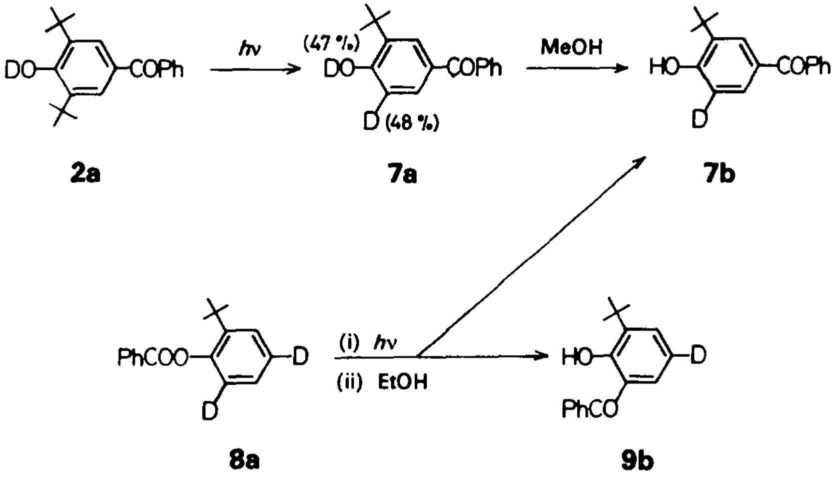
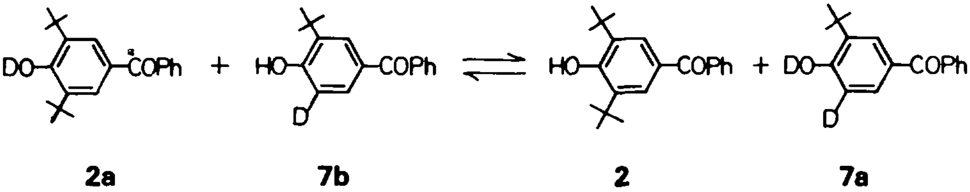
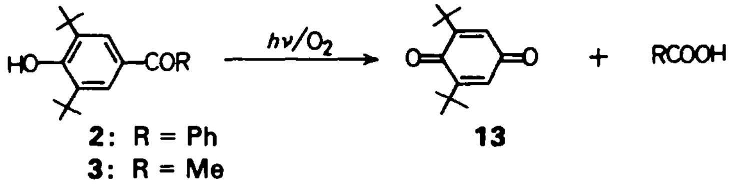
† Piperylene has been shown to quench only triplet states of ketones.[11]



in the equation below. The non-deuterated ketone **2** thus formed is converted to the non-deuterated product **7**.

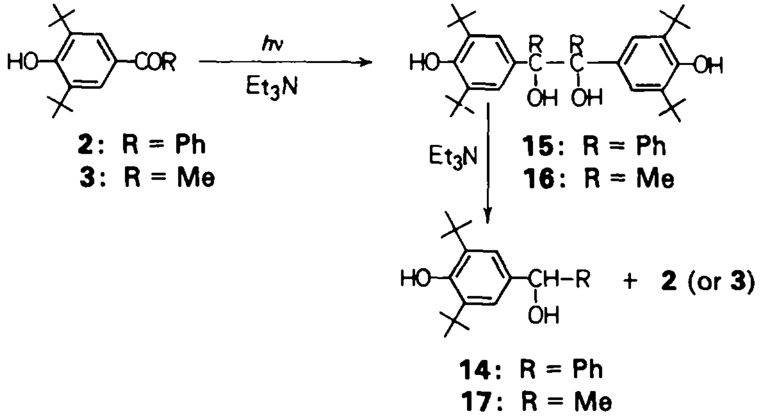


Photooxygenation of **2** *and* **3**. In order to obtain further information on the excited states of **2** and **3**, the photooxygenation of **2** and **3** was carried out. Irradiation of **2** in cyclohexane under bubbling oxygen resulted in facile oxidative cleavage to give 2,6-di-t-butyl-*p*-benzoquinone (**13**) and benzoic acid in 11·5 and 11·3% yield, respectively. On the other hand on photooxygenation of **2** in isopropyl alcohol under the same conditions **2** was recovered quantitatively. Photooxygenation of **3** in cyclohexane–benzene also resulted in facile oxidative cleavage to give 2,6-di-t-butyl-*p*-benzoquinone (**13**) in 13% yield and acetic acid was detected by a GLC analysis from the reaction mixture.



On the other hand, 4-hydroxybenzophenone and 4-hydroxyacetophenone on photooxygenation in benzene did not undergo cleavage reactions to give *p*-benzoquinone and the corresponding acids but gave only polymeric material.

Photoreduction of **2** *and* **3** *in triethylamine.* Photoreduction of benzophenone and its derivatives in an amine solvent are known to proceed efficiently to give the corresponding pinacols, and mechanisms, which differ from that of the photoreduction of benzophenone in isopropyl alcohol, have been proposed.[13] It is, therefore, of interest to see whether photoreduction in triethylamine occurs with **2** and **3** which were shown to undergo de-t-butylation *via* the triplet state. Irradiation of **2** in triethylamine yielded 3,5- di-t-butyl-4-hydroxybenzhydrol (**14**) in 30% yield. The structure of **14** was assigned from its spectral properties and was confirmed by synthesis by the reduction of **2** with LAH. The formation of the benzhydrol **14** can be explained by the triethylamine-catalyzed disproportionation of the initially formed pinacol **15** to **2** and **14**.[13b] In accordance with this explanation, irradiation of **3** in triethylamine yielded the corresponding pinacol (**16**; 33% yield) which was converted by further treatment with triethylamine to **3** and 3,5-di-t-butyl-4-hydroxy-α-methylbenzyl alcohol (**17**).

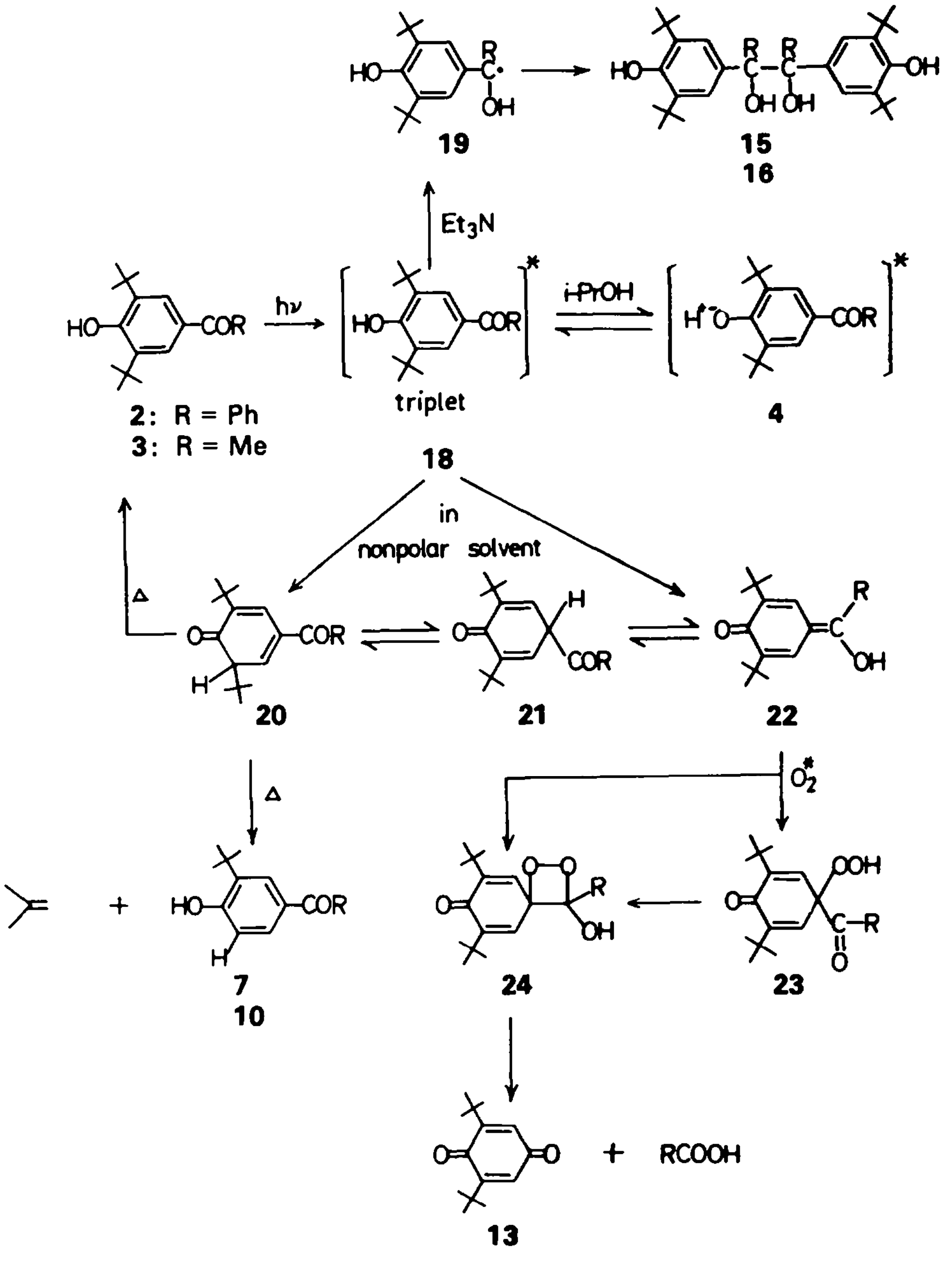


Mechanistic consideration. As a summary of the results, the dependence of the photochemical behaviour of the 3,5-di-t-butyl-4-hydroxyphenyl ketones **2** and **3** on the environment is as follows: (i) In isopropyl alcohol, they are recovered unchanged. (ii) In a non-polar hydrocarbon solvent, de-t-butylation occurs predominantly, although in the case of **2** hydrogen abstraction occurs to some extent. Since the disappearance of **2** and **3** in a nonpolar solvent is effectively quenched by piperylene, the triplet state must be responsible for the de-t-butylation reaction. (iii) The triplet nature of the excited state of **2** and **3** is well manifested by the photoreduction in triethylamine leading to **14** and **16**, respectively. (iv) The photooxygenation of **2** and **3** leading to an oxidative cleavage at the aryl-CO bond is also considered to involve the triplet state because the reaction proceeds in a nonpolar solvent as in the case of (ii). (v) Furthermore, a cyclohexane solution of **2** or **3** turns yellow on irradiation and the yellow colour fades gradually after the interruption of irradiation.

The above results can be rationalized by pathways illustrated in Chart I.

The photochemical unreactivity of **2** and **3** in isopropyl alcohol may be attributable to the formation of the unprotonated form **4** of their triplet **18** as suggested by Porter and Suppan[8] in the case of 4-hydroxybenzophenone. The unprotonated form would be highly stabilized by a protic solvent such as isopropyl alcohol and acetic acid. In the presence of triethylamine, however, the triplet state **18** is capable of electron

CHART I

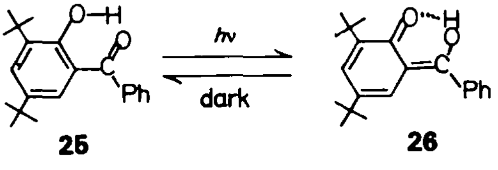


abstraction from the nitrogen lone pair of the amine followed by proton transfer to form the corresponding pinacol (**15** and **16**) *via* a ketyl radical **19**.[13c]

The photochemical de-t-butylation reaction was shown by the quenching experiments to involve the triplet excited state of **2** and **3**. This result and the photochromic behaviour of **2** and **3** strongly suggest that the de-t-butylation occurs *via* a phototautomer **20**, namely the orthoketone tautomer of the phenols **2** and **3**. It has been shown by Miller *et al.*[14] and by Matsuura *et al.*[15] that such a 2,5-cyclohexadienone bearing a t-Bu group at position 6 easily undergoes thermal de-t-butylation to give a phenol. Thus, the phototautomer **20** thermally loses isobutylene to form the 3-t-butyl-4-hydroxyphenyl ketones (**7** and **10**). This mechanism is quite consistent with the experiments, in which the D atom of the deuterioxy analog (**2a**) of **2** was shown to be incorporated into position 5 of **7**. Alternatively, the photoautomer **20** would thermally revert to the parent ketones (**2** and **3**).

We obtained evidence for another type of tautomerization leading to a quinone methide phototautomer **22** which can explain the photooxygenation of **2** and **3** leading to the benzoquinone **13** and an acid RCOOH. The photooxygenation probably involves a singlet excited oxygen molecule[16] which may be formed by energy transfer from the triplet excited state **18** to the ground state oxygen molecule. Singlet oxygen thus formed can add to **22** to give a ketone hydroperoxide **23** which then rearranges to a 4-membered cyclic peroxide **24**.† Finally, **24** cleaves to the benzoquinone **13** and an acid. This type of cleavage has an analogy in the photosensitized oxygenation of certain 3-hydroxyflavones.[19] Two possible pathways for the formation of **22** were considered. One is the tautomerization of **20** *via* a phototautomer **21**, namely the *para*-ketone tautomer of the parent phenol, for the presence of which we have no evidence at present. The other is the direct tautomerization from the triplet state **18**. We can offer no reasonable explanation for the polymer formation in the photooxygenation of 4-hydroxybenzophenone and 4-hydroxyacetophenone.

Photoreaction of 3,5-di-t-butyl-2-hydroxybenzophenone (**25**). 2-Hydroxybenzophenones are known to undergo photoenolization (as **25** → **26**).[20] Considering the results obtained with the 3,5-di-t-butyl-4-hydroxyphenyl ketones **2** and **3**, it appeared to be of interest to investigate the effect of t-Bu substitution on the photochemical behaviour of 2-hydroxybenzophenone. However, on irradiation under various conditions, 3,5-di-t-butyl-2-hydroxybenzophenone (**25**) was recovered unchanged. The irradiation was carried out in methanol and also in cyclohexane either under nitrogen or oxygen. The lack of photoreactivity of **25** is rationalized by the formation of a photoenol **26**, which is easily converted to the starting material, as in the case of 2-hydroxybenzophenone itself. It has been suggested that 2-hydroxybenzophenones probably undergo photoenolization *via* the excited singlet state since they show no phosphorescence.[8, 21] The same may hold true for the photochemical behaviour



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† A direct formation of **24** from **22** is also possible. Other possible mechanisms, which involve the addition of singlet oxygen to the parent ketone (**2** and **3**) or hydrogen abstraction from the parent ketone followed by the attack of the ground state oxygen on the resulting phenoxy radical, were also taken into consideration. Such mechanisms have been discussed[17] but considering the fact that various photoenols undergo photooxygenation,[1, 18] the mechanism illustrated in Chart I appears most plausible.

of **25**. It is also reasonable to assume that the photoenol **26** may not undergo further tautomerization like 3,5-di-t-butyl-4-hydroxybenzophenone (**2**), if any, since the photoenol is highly stabilized by intramolecular H-bonding.

In comparison to the photochemical behaviour of **25**, the photolysis of 2-hydroxy-5-methylbenzophenone[21] was carried out. The compound was recovered unchanged on irradiation in cyclohexane under oxygen, in accordance with the result obtained with **25**.

EXPERIMENTAL

All m.p.'s are uncorrected. IR spectra were obtained by a Japan Spectroscopic Co., Model IRS spectrometer. The NMR spectra were obtained on a Japan Electron Optics C-60-H Spectrometer with TMS as an internal standard. Elemental analyses were performed at the Elemental Analysis Center of Kyoto University. Mass spectra were recorded by the Mass Spectroscopic Analysis Laboratory, Faculty of Pharmaceutical Science, Kyoto University. All irradiations were made with a 450-W high-press Hg vapour lamp (Ushio Type UM 450) surrounded by a Pyrex cooling jacket under bubbling N_2 at room temp unless otherwise indicated.

Photolysis of 3,5-*di-t-butyl-4-hydroxybenzophenone* (**2**)

A. *In isopropyl alcohol.* A soln of **2**[22] (1·00 g) in 250 ml isopropyl alcohol was irradiated for 15 hr. Evaporation of the solvent under reduced press gave the unreacted **2** quantitatively as colourless crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis.

B. *In acetic acid.* A soln of **2** (1·00 g) in 400 ml AcOH was irradiated for 10 hr. Evaporation of the solvent under reduced press gave the unchanged **2** quantitatively which was identified by comparison of the IR spectrum with that of an authentic sample.

C. *In cyclohexane.* A soln of **2** (3·00 g) in 450 ml. cyclohexane was irradiated for 27 hr. The exhaust gas was led to a 20 ml test tube containing ice-cooled Br_2 (10 ml). The test tube contents were treated with an $NaHSO_3$aq and extracted with ether. The ether layer was washed with water and dried ($NaSO_4$). Evaporation of the solvent gave 1,2-dibromoisobutane (425 mg, 23%) as a slightly coloured oil which was identified by comparison of the IR spectrum with that of an authentic sample and by GLPC analysis. In the course of the irradiation fine crystals were separated from the soln. The crystals were collected by filtration to give **7** (500 mg) as fine leaflets: m.p. 179–180°, which were identified by comparison of the IR spectrum with that of an authentic sample prepared below. The filtrate was evaporated to give a viscous residue which was dissolved in pet. ether and chromatographed on a silica gel column (60 g). Elution with pet. ether gave the cyclohexane adduct (516 mg, 15·5%) as a slightly coloured solid. Crystallization from MeOH gave colourless needles: m.p. 129–131°; IR (KBr) 1700 cm^{-1} (C=O). (Found: C, 82·51, H, 9·26. Calc. for $C_{27}H_{36}O_2$: C, 82·65; H, 9·18).

Further elution with benzene gave the unreacted **2** (350 mg). Further elution with $CHCl_3$ gave **7** (545 mg) as crystals. The total yield of **7** amounted to 1045 mg (50%).

A soln of **7** (50 mg) in 10 ml benzene was refluxed with $AlCl_3$ (1·00 g) for 3 hr. The reaction mixture was poured onto a mixture of ice and conc HCl and extracted with ether. The ether layer was washed with water, dried (Na_2SO_4), and evaporated to give yellow crystals. Recrystallization from cyclohexane gave **1** (23 mg) as colourless needles which were identified by comparison of the IR spectrum with that of an authentic sample.

D. *In triethylamine.* A soln of **2** (1·500 g) in 400 ml Et_3N was irradiated for 22 hr. Evaporation of the solvent under reduced press gave a dark brown residue which was dissolved in benzene-pet. ether (1 : 1) and chromatographed on a silica gel column (40 g). Elution with benzene-pet. ether (1 : 1) gave recovered **2** (576 mg, 38%) as slightly yellow crystals. Further elution with benzene gave **14** as white crystals (316 mg, 30%). Recrystallization from pet. ether gave colourless fine needles: m.p. 124–125°; IR (Nujol) 3350 (OH) and 3370 cm^{-1} (OH); NMR ($CDCl_3$) δ 7·0–δ 7·30 (m, 7), 5·67 (s, 1, $\rangle C\underline{H}{-}OH$), 5·05 (s, 1, $O\underline{H}$), 2·10 (s, 1, $O\underline{H}$) and 1·87 ppm (s, 18, $(C\underline{H}_3)_3C$). (Found: C, 79·95; H, 9·33. Calc. for $C_{21}H_{28}O_2$: C, 80·73; H, 9·03).

The IR spectrum of **14** was identical with that of an authentic sample prepared below.

3,5-*Di-t-butyl-4-hydroxybenzhydrol* (**14**)

A soln of **2** (250 mg, 0·8 mmol) in 20 ml ether was stirred with LAH (70 mg, 1·8 mmole) at room temp for 10 min. The reaction mixture was treated with dil HCl and extracted with ether. The ether layer was dried (Na_2SO_4) and evaporated to give a white solid. Crystallization from pet. ether gave **14** as colourless needles (200 mg, 80%): m.p. 124–125°.

Photolysis of 3,5-*di-t-butyl-4-hydroxyacetophenone*(**3**)

A. *In isopropyl alcohol.* A soln of **3**[23] (2·00 g) in 450 ml isopropyl alcohol was irradiated for 18·5 hr. Evaporation of the solvent under reduced press gave quantitatively the unreacted **3** as white crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis.

B. *In cyclohexane.* A soln of **3** (1·50 g) in 350 ml cyclohexane was irradiated for 38 hr. Evaporation of the solvent under reduced press gave a dark brown oil which was dissolved in benzene-$CHCl_3$ (1 : 1) and chromatographed on a silica gel column (40 g). Elution with $CHCl_3$ gave the recovered **3** (800 mg) as white crystals which were identified by comparison of the IR spectrum with that of an authentic sample. Further elution with $CHCl_3$ gave **10** as slightly brown crystals (416 mg, 95% based on reacted **3**). Recrystallization from benzene-n-hexane gave colourless needles: m.p. 175–176°. The IR spectrum of **10** was identical with that of an authentic sample prepared below.

A soln of **10** (40 mg) in 50 ml benzene was refluxed with $AlCl_3$ (700 mg) for 6 hr. The reaction mixture was poured onto a mixture of ice and HCl and extracted with ether. The ether layer was dried (Na_2SO_4) and evaporated to give a brown oil which crystallized on standing at room temp. Recrystallization from n-hexane gave 4-hydroxyacetophenone (15 mg) as slightly coloured needles: m.p. 109–110°. The IR spectrum was identical with that of an authentic sample.

C. *In triethylamine.* A soln of **3** (1·500 g) in 400 ml Et_3N was irradiated for 35 hr. Removal of the solvent under reduced press gave a brown viscous oil which was dissolved in benzene-pet. ether (1 : 1) and chromatographed on a silica gel column (40 g). Elution with benzene-pet. ether (1 : 1) gave the recovered **3** as white crystals (625 mg, 41·6%) which were identified by comparison of the IR spectrum with that of an authentic sample. Further elution with benzene gave the corresponding pinacol **16** (290 mg, 33%) as slightly coloured crystals. Recrystallization from pet. ether gave colourless crystals: m.p. 216–217°; IR (Nujol) 3600 (OH) and 3450 cm^{-1} (OH); NMR ($CDCl_3$) δ 1·32, 1·35 (s, 36, $C\underline{H}_3C$), 1·50, 1·57 (s, 6, $C\underline{H}_3$), 1·90, 2·40 (broad signal, 2, $O\underline{H}$), 4·93, 4·97 (s, 2, $O\underline{H}$) and 6·85, 6·82 ppm (s, 4). (Found: C, 77·05; Calc. for $C_{32}H_{50}O_4$: C, 77·06; H, 10·11).

A soln of **16** (10 mg) in 5 ml Et_3N was allowed to stand at room temp for 48 hr. TLC analysis of the reaction mixture showed that it consisted of **3** and **17**.

3,5-*Di-t-butyl-4-hydroxy-α-methylbenzyl alcohol* (**17**). A soln of **3** (496 mg, 2 mmol) in 20 ml ether was stirred with LAH (200 mg, 5·0 mmol) at room temp for 10 min. The reaction mixture was treated with dil HCl and extracted with ether. The ether layer was dried (Na_2SO_4) and evaporated to give a slightly coloured solid. Crystallization from pet. ether gave **17** as colourless crystals (180 mg, 36%): m.p. 104–105°; IR (Nujol) 3430 (OH) and 3150 cm^{-1} (OH): NMR ($CDCl_3$) δ 1·44 (s, 18, $(C\underline{H}_3)_3$), 1·47 (d, 3, $C\underline{H}_3$), 1·63 (s, 1, $O\underline{H}$), 4·80 (q, 1, $>C\underline{H}{-}CH_3$). 5·15 (s, 1, $O\underline{H}$), and 7·36 ppm (s, 2, aromatic protons). (Found: C, 76·12; H, 10·55. Calc. for $C_{16}H_{26}O_2$: C, 76·75; H, 10·47).

3,5-*Di-t-butyl-4-methoxybenzophenone* (**5**)

To a soln of **2** (2·97 g, 0·01 mol) in 20 ml dry DMSO was added NaH (0·50 g, 0·02 mol) under stirring at room temp. After evolution of H_2 gas had ceased, a large excess MeI (5·00 g) was added and the mixture was stirred for 20 min at room temp. The reaction mixture was poured into ice-water, and extracted with pet. ether. The pet. ether layer was washed with water, dried (Na_2SO_4), and concentrated to about 50 ml. The crystals which separated were collected by filtration (1·825 g), and were characterized as starting **2** by IR and TLC analyses. The filtrate was chromatographed on a silica gel column (30 g). Elution with benzene-pet. ether (1 : 1) yielded **5** (470 mg) as colourless plates: m.p. 59–60°; IR (Nujol) 1650 cm^{-1} (C=O); NMR ($CDCl_3$) δ 7·25–δ 7·80 (m, 7, aromatic protons), 3·67 (s, 3, CH_3O), and 1·42 ppm (s, 18, $(CH_3)_3C$). (Found: C, 81·67; H, 8·72. Calc. for $C_{22}H_{28}O_2$: C, 81·44; H, 8·70).

Photolysis of 3,5-*di-t-butyl-4-methoxybenzophenone* (**5**)

A. *In isopropyl alcohol.* A soln of **5** (200 mg) in 400 ml isopropyl alcohol was irradiated for 4 hr. Evaporation of the solvent under reduced press gave a colourless oil. Preparative TLC on silica gel gave the corresponding pinacol **6** as white crystals (110 mg, 55%): m.p. 70–75°; IR(Nujol) 3530 cm^{-1} (OH); NMR ($CDCl_3$) δ 1·22 (s, 36, $(C\underline{H}_3)_3C$), 2·92 (s, 1, O$\underline{H}$), 2·88 (s, 1, O$\underline{H}$), 3·05 (s, 6, $OC\underline{H}_3$) and 7·02–7·20 ppm (m, 14). (Found: C, 80·21, H, 9·06. Calc. for $C_{44}H_{58}O_4$: C, 81·19; H, 8·98).

B. *In cyclohexane.* A soln of **5** (150 mg) in 400 ml cyclohexane was irradiated for 10 hr. Removal of the solvent under reduced press gave a colourless viscous oil. Preparative TLC on silica gel gave the corresponding pinacol **6** (45 mg, 30%) as white crystals which were identical with **6** obtained above.

Quenching experiments of 3,5-*di*-t-*butyl-4-hydroxybenzophenone* **2** *and* 3,5-*di*-t-*butyl-4-hydroxyacetophenone* **3** *with* 1,3-*pentadiene in cyclohexane*

1,3-Pentadiene was purified by distillation prior to use. The compound **2** (2·5 × 10^{-4} mol) was placed in a 20 ml Pyrex tube. To two of the Pyrex tubes was added 340 mg (5 × 10^{-4} mol) and 2·720 g (4·0 × 10^{-4} mol) of 1,3-pentadiene, respectively. One tube without any added 1,3-pentadiene was used as a control and to these three Pyrex tubes was added cyclohexane until the total volume amounted to 10 ml. After N_2 gas had been bubbled for 30 min before irradiation, the three Pyrex tubes were sealed with glass stoppers, placed on a cylindrical wall and irradiated for 10 hr with a 450-W. high-press. Hg vapour lamp (Ushio, Type UM 450) with a Pyrex cooling jacket set at the center of the cylinder. After irradiation, **3** (62·0 mg, 2·5 × 10^{-4} mol) was added to each of the tubes as an internal standard and the solvent was removed. The residue was analyzed by GLPC on a DC-550 silicone on celite column at oven temp 210° and a He press. of 2·0 Kg.cm^{-2}. A set of tubes was prepared as above with **3** (62·0 mg, 2·5 × 10^{-4} mol) instead of **2**. 1,3-Pentadiene was added to each of two tubes to the extent of 340 mg and 2·720 g. **2** was used as an internal standard for the GLPC analysis of **3**. The results are summarized in Table 1.

Photolysis of 3-t-*butyl-4-hydroxybenzophenone* (**7**). A soln of **7** (145 mg) in 450 ml cyclohexane was irradiated for 10 hr. Evaporation of the solvent under reduced press gave a brown viscous oil which was shown by TLC to consist of at least ten products and was not further investigated.

Photo-Fries rearrangement of 2-t-*butylphenyl benzoate* (**8**) *to* **7** *and* **9**. A soln of **8** (2·50 g) in 200 ml benzene was irradiated with a 10-W low-press Hg vapour lamp (Vycor filter) for 12·5 hr. Evaporation of the solvent gave a brown residue which was dissolved in benzene and chromatographed on a silica gel column (60 g). Elution with benzene gave **9** as a viscous oil (880 mg, 35%). Vaccum distillation gave a pale yellow viscous oil: b.p. 92° (10^{-3} mm); IR 1610 cm^{-1} (C=O); NMR ($CDCl_3$) δ 12·55 (s, 1, O$\underline{H}$), 7·80 6·55 (m, 8) and 1·47 ppm (s, 9, $(C\underline{H}_3)_3C$). (Found: C, 80·05; H, 6·94. Calc. for $C_{17}H_{18}O_2$: C, 80·28; H, 7·13).

Further elution with $CHCl_3$ gave **7** as slightly coloured crystals (500 mg, 20%). Recrystallization from n-hexane-benzene gave colourless needles: m.p. 179–180°; IR (Nujol) 3350 (OH) and 1620 cm^{-1} (C=O); NMR ($CDCl_3$) δ 6·72 (s, 1, O$\underline{H}$), 7·65–6·60 (m, 8) and 1·37 ppm (s, 9, $(C\underline{H}_3)_3C$). (Found: C, 80·32; H, 7·17. Calc. for $C_{17}H_{18}O_2$: C, 80·28; H, 7·13).

Photo-Fries rearrangement of 2-t-*butylphenyl acetate* (**11**) *to* **10** *and* **12**

A soln of **11** (3·75 g) in 200 ml benzene was irradiated with a 10-W low-press Hg vapour lamp (Vycor filter) under bubbling N_2 for 30 hr. Evaporation of the solvent under reduced press gave a dark brown oil which was dissolved in benzene and chromatographed on a silica gel column (80 g). Elution with benzene gave **12** as a brownish yellow oil (1·00 g, 26%). Vacuum distillation gave a pale yellow oil: b.p. 87° (5 mm); IR (Nujol) 1630 cm^{-1} (C=O); NMR ($CDCl_3$) δ 7·65–6·55 (m, 3), 2·60 (s, 3, $C\underline{H}_3CO$) and 1·40 ppm (s, 9, $(C\underline{H}_3)_3C$). (Found: C, 75·59; H, 8·67. Calc. for $C_{12}H_{16}O_2$: C, 74·97; H, 8·39).

Further elution with $CHCl_3$ gave **10** as slightly brown crystals (900 mg, 24%). Recrystallization from n-hexane-benzene gave colourless needles: m.p. 174–175°; IR (Nujol) 1640 cm^{-1} (C=O); NMR ($CDCl_3$) δ 6·60–7·90 (m, 3), 2·52 (s, 3, $C\underline{H}_3CO$), and 1·39 ppm (s, 9, $(C\underline{H}_3)_3C$). (Found: C, 74·70; H, 8·24. Calc. for $C_{12}H_{16}O_2$: C, 74·97; H, 8·39).

3,5-*Di*-t-*butyl-4-deuterioxybenzophenone* (**2a**)

A soln of **2** (800 mg) dissolved at 50° in 3 ml monodeuteriomethanol (D enrichment 99%) was placed in a stoppered 10 ml flask and allowed to stand at room temp. The colourless needles which separated were collected by filtration to give the partly deuterated **2** (530 mg). The crystals were treated again in the same manner to give **2a** (490 mg) as colourless needles: m.p. 128–130°; IR (Nujol) 2620 cm^{-1} (OD).

Photolysis of **2a**

A soln of **2a** (250 mg) in 20 ml dry cyclohexane was placed in a Pyrex tube. N_2 gas was bubbled for 30 min prior to irradiation and the tube sealed with a glass stopper was then externally irradiated with 450-W high-press Hg vapour lamp (Ushio Type UM 450) for 44 hr. After irradiation the tube was allowed to stand at room temp over night. Fine crystals which separated were collected to give **7a** as colourless crystals (44 mg): m.p. 174–176°. The D enrichment of the OH group of **7a** was estimated as 57% by NMR analysis. The IR spectrum of **7a** (KBr) showed new bands at 2490, 992, 897, 856, and 782 cm^{-1} in addition to the IR spectrum of **7**. Treatment of **7a** with MeOH gave **7b**. The D enrichment of **7b** was estimated as 48% by mass spectroscopic analysis. The IR spectrum of **7b** (KBr) showed new bands at 992, 897, 856, and 782 cm^{-1} in addition to the IR spectrum of **7**.

2-t-*Butyl-4,6-dideuteriophenol*

The deuteration of 2-t-butylphenol was carried out according to the procedure of Chapman *et al.*[24] A mixture of 2-t-butylphenol (7·95 g, 0·05 mol), NaOH (1·0 g, 0·025 mol) and D_2O (20 ml, 1·0 mol) was heated in a sealed tube at 90° for 20 hr. After cooling, the mixture was acidified with HCl and extracted with ether. The ether was evaporated and the recovered phenol was deuterated again in the same manner to give 2-t-butyl-4,6-dideuteriophenol (5·3 g) as a colourless oil: b.p. 115–116° (28 mm). The D enrichment of the phenol was estimated as 70% by mass spectroscopic analysis.

2-t-*Butyl-4,6-dideuteriophenyl benzoate* (**8a**)

A soln of 2-t-butyl-4,6-dideuteriophenol (5·3 g, 0·035 mol) and benzoyl chloride (5·59, 0·04 mol) in 15 ml dry pyridine was allowed to stand at 60° for 1 hr. The reaction mixture was poured into water and extracted with ether. The ether layer was washed with $NaHCO_3$ aq, dried (Na_2SO_4) and evaporated to give a slightly yellow solid. Crystallization from EtOH-water gave **8a** (4·5 g) as colourless crystals: m.p. 71–72°.

Photolysis of **8a**

A soln of **8a** (2·00 g) in 200 ml benzene was irradiated with a 10-W low-press Hg vapour lamp (Vycor filter) under bubbling N_2 for 8 hr. Removal of the solvent under reduced press gave a brownish red residue which was dissolved in pet. ether–benzene (1 :1) and chromatographed on a silica gel column (50 g). Elution with pet. ether–benzene (1:1) have **9b** as a brown yellow oil (600 mg, 30%). Vacuum distillation gave a pale yellow viscous oil: b.p. 92° (10^{-3} mm). The D enrichment of **9b** was estimated as 67% by mass spectroscopic analysis. Further elution with $CHCl_3$ gave **7b** (316 mg, 15·8%) as slightly brown crystals. Recrystallization from n-hexane–benzene gave colourless crystals: m.p. 174–175°. The D enrichment of **7b** was estimated as 69% by mass spectroscopic analysis. The IR spectrum of **7b** thus obtained was virtually identical with that of **7b** obtained by the photolysis of **2a**. The mass spectrum of **7b** thus obtained was quite similar to that of **7b** obtained by the photolysis of **2a**.

Photooxygenation

A. 3,5-*Di-*t-*butyl-4-hydroxybenzophenone* (**2**) *in isopropyl alcohol.* A soln of **2** (2·00 g) in 400 ml isopropyl alcohol was irradiated under bubbling O_2 for 3 hr. The reaction mixture was evaporated under reduced press to give the recovered **2** as slightly coloured crystals which were identified by comparson of the IR spectrum with that of an authentic sample and by TLC analysis.

B. **2** *in Cyclohexane.* A soln of **2** (2·00 g) in 400 ml cyclohexane was irradiated under bubbling O_2 for 3·5 hr. The reaction mixture was evaporated under reduced press to give a brownish oil which was dissolved in pet. ether and chromatographed on a silica gel column (50 g). Elution with pet. ether-benzene (5 :1) gave **13** as an orange solid (166 mg, 11·5%) which was identified by comparison of the IR spectrum with that of an authentic sample.[25] Further elution with benzene yielded benzoic acid as colourless crystals (100 mg, 11·3%) which were identified by comparison of the IR spectrum with that of an authentic sample.

C. 3,5-*Di-*t-*butyl-4-hydroxyacetophenone* (**3**) *in cyclohexane-benzene.* A soln of **3** (2·00 g) in a mixture of cyclohexane (340 ml) and benzene (60 ml) was irradiated under bubbling O_2 for 5·5 hr. Evaporation of the solvent under reduced press gave a brownish oil which was dissolved in pet. ether-benzene (1 : 1) and chromatographed on a silica gel column (50 g). Elution with pet. ether-benzene (1 : 1) yielded **13** as orange crystals (240 mg, 13%) which were identified by comparison of the IR spectrum with that of an authentic sample. GLPC analysis of the reaction mixture showed the presence of AcOH.

D. 4-*Hydroxybenzophenone* (**1**) *in benzene.* A soln of **1** (1·00 g) in 400 ml benzene was irradiated under bubbling O_2 for 2 hr. The brown ppt which separated from the reaction mixture was collected by filtration to give a polymeric brown powder (690 mg). The filtrate was evaporated under reduced press to give a viscous brown oil which was dissolved in benzene and chromatographed on a silica gel column (30 g).

Elution with $CHCl_3$ gave the unreacted **1** (473 mg) as slightly yellow crystals which were identified by comparison of the IR spectrum with that of an authentic sample. Benzoic acid and *p*-benzoquinone were not detected by TLC analysis.

E. *4-Hydroxyacetophenone in benzene.* A soln of 4-hydroxyacetophenone (1·00 g) in 400 ml benzene was irradiated under bubbling O_2 for 50 min. A brown ppt which separated from the reaction mixture was collected by filtration to give a brown polymeric powder (86 mg). The filtrate was evaporated under reduced press to give the unreacted 4-hydroxyacetophenone (940 mg) as slightly yellow crystals which was identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis. *p*-Benzoquinone was not detected by TLC analysis of the reaction mixture.

3,5-Di-t-butyl-2-hydroxybenzophenone (**25**)

2,4-Di-t-butylphenyl benzoate was prepared by the benzoylation (Schotten–Bauman) of 2,4-di-t-butylphenol. A solution of 2,4-di-t-butylphenyl benzoate (6·0 g) in 200 ml benzene was irradiated with a 10-W low-press Hg vapour lamp (Vycor filter) under bubbling N_2 (42 hr). The reaction mixture was evaporated under reduced press to give a brown viscous oil which was dissolved in pet. ether and chromatographed on a silica gel column (150 g). Elution with pet. ether yielded **25** (1·52 g, 31·8 % based on the reacted ester) as a yellow solid. Crystallization from MeOH gave pale yellow prisms: m.p. 61–62°; IR (Nujol) 1615 cm^{-1} (C=O), NMR ($CDCl_3$) δ 12·55 (s, 1, O$\underline{H}$), 7·30–7·80 (m. 7, aromatic protons), 1·45 (s, 9, $(CH_3)_3C$), and 1·22 ppm (s, 9, $(C\underline{H}_3)_3C$). (Found: C, 81·51; H, 8·70. Calc. for $C_{21}H_{26}O_2$: C, 81·25; H, 8·44).

Further elution with benzene gave the unreacted ester (1·22 g, 20·3%) as slightly yellow crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis.

3,5-Di-t-butyl-2-hydroxybenzophenone (**25**)

A. *Photooxygenation in cyclohexane.* A soln of **25** (500 mg) in 300 ml cyclohexane was irradiated under bubbling O_2 (9 hr). Evaporation of the solvent under reduced press gave unreacted **25** quantitatively as yellow crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis.

B. *Photolysis in methanol.* A soln of **25** (1·00 g) in 400 ml MeOH was irradiated for 12 hr under bubbling N_2. Evaporation of the solvent under reduced press yielded quantitatively unreacted **25** as yellow crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis.

C. *Photolysis in cyclohexane.* A soln of **25** (1·00 g) in 400 ml cyclohexane was irradiated under bubbling N_2 for 16 hr. Evaporation of the solvent under reduced press gave quantitatively unreacted **25** as yellow crystals which were identified by a comparison of the IR spectrum with that of an authentic sample by TLC analysis.

Photooxygenation of 2-hydroxy-5-methylbenzophenone

A. *In methanol.* A soln of the compound[26] (2·00 g) in 400 ml methanol was irradiated under bubbling O_2 for 11 hr. Evaporation of the solvent under reduced press gave quantitatively unreacted starting material as yellow crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TCC analysis.

B. *In cyclohexane.* A soln of the compound (2·00 g) in 400 ml cyclohexane was irradiated under bubbling O_2 for 13 hr. Evaporation of the solvent under reduced press yielded quantitatively unreacted starting material as yellow crystals which were identified by comparison of the IR spectrum with that of an authentic sample and by TLC analysis.

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