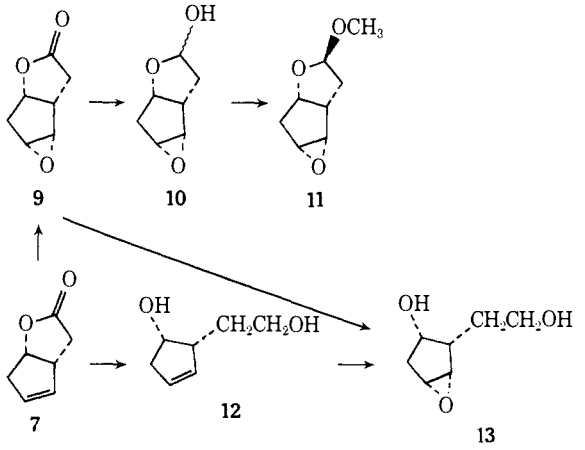
5 and its antipode was established by catalytic hydrogenation to the dihydro derivatives which were oxidized with standard Jones reagent[8] to yield ketone **8**, $[\alpha]_D$ −122° and its antipode, $[\alpha]_D$ +123°. Ketone **8** exhibited a strong negative Cotton effect (ORD amplitude a = −91, centered at 296 nm) and was assigned the *S* absolute configuration whereas the antipodal ketone showed a strong positive Cotton effect (ORD amplitude a = +94, centered at 296 nm) and was assigned the *R* absolute configuration.[6]

Lactone **7** formed the *cis*-epoxy lactone **9**, mp 76–77°, $[\alpha]_D$ −115° ($CHCl_3$), in 80% yield on exposure to commercial 40% peracetic acid[2] in sodium acetate–acetic acid buffer (Scheme II). The prostaglandin intermediate **11**, $[\alpha]_D$ −180° ($CHCl_3$), was prepared by treating epoxy lactone **9** with diisobutylaluminum hydride[2] at −78° to yield epoxy lactol **10**, mp 65–66°, $[\alpha]_D$ −4.4° ($CHCl_3$, rotation at equilibrium), which was immediately exposed to methanolic boron trifluoride[2] (75% overall yield). Racemic epoxy acetal **11** has been converted into *dl*-prostaglandin $F_{2\alpha}$ by Corey and Noyori.[2]

Scheme II[a]



[a] See footnote *a* of Scheme I.

Lactone **7** also yielded the optically active form of the Fried prostaglandin intermediate **13**,[3,4] $[\alpha]_D$ −5.0°, in greater than 90% overall yield by reduction ($LiAlH_4$, ether, 25°) to diol **12**, $[\alpha]_D$ −74°, which was cleanly epoxidized with *m*-chloroperbenzoic acid in methylene chloride containing sodium bicarbonate at 0°. Epoxy diol **13** was homogeneous in a wide variety of chromatographic systems and yielded a single epoxy diacetate with acetic anhydride. The relative stereochemistry of **13** was initially assigned on the basis of its 100-MHz nmr spectrum and the known hydroxy-directing effect of epoxidation of homoallylic alcohols.[8] This assignment was confirmed by reducing the *cis*-epoxy lactone **9** directly to epoxy diol **13** ($LiAlH_4$, THF, 0°, 33% yield).

In conclusion, short asymmetrically induced syntheses were devised for several key prostaglandin intermediates beginning with cyclopentadiene (**3**). These results open additional routes for the facile preparation of optically active prostaglandins in substantial quantities.

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John J. Partridge,* Naresh K. Chadha, Milan R. Uskoković
Chemical Research Department, Hoffmann-La Roche Inc.
Nutley, New Jersey 07110
Received July 25, 1973

Solvent Effect in the Photoreduction of Decafluorobenzophenone by 2-Propanol. Reinterpretation of the Light-Intensity Effect in the Benzophenone–2-Propanol System

Sir:

Aromatic ketones in the $^3(n_1\pi^*)$ state abstract hydrogen[1] from solvents and yield pinacols by a ketyl radical recombination reaction. Decafluorobenzophenone (**1**) reacts in the $^3(n_1\pi^*)$ state;[2,3] however, the ketyl radical[4] formed in 2-propanol, cyclohexane, and alkyl aromatics does not lead to the formation of eicosafluorobenzopinacol (**2**).[2,5] This anomaly has been explained by the importance of competitive radical cross-combination reactions[2] in cyclohexane and alkyl aromatics. Evidence is presented in this paper to show that a quantitative yield of **2** is obtained when **1** is photolyzed in perfluoroalkane containing 2-propanol.[6] The earlier conclusion[7] that triplet quenching by radicals was occurring in the benzophenone–2-propanol system appears unjustified;[8] therefore, further studies are reported to clarify the existing ambiguity.

Experimental techniques were similar to those used previously.[2] When degassed solutions of **1** (0.01 and 0.02 *M*) in perfluoromethylcyclohexane containing 2-propanol (0.005–to 0.04 *M*) were irradiated with 366-nm light, the principal products were **2** and acetone. Typical results are shown in Table I. Decafluorobenzhydrol (**3**), which is the principal product[5] when

(1) (a) J. N. Pitts, Jr., R. L. Letsinger, R. P. Taylor, J. M. Patterson, G. Recktenwald, and R. B. Martin, *J. Amer. Chem. Soc.*, **81**, 1068 (1959); (b) G. S. Hammond, W. P. Baker, and W. M. Moore, *J. Amer. Chem. Soc.*, **83**, 2795 (1961); (c) G. Porter and F. Wilkinson, *Trans. Faraday Soc.*, **57**, 1686 (1961); (d) A. Beckett and G. Porter, *Trans. Faraday Soc.*, **59**, 2038 (1963); (e) A. Schönberg, "Preparative Organic Chemistry," Springer-Verlag, New York, N. Y., 1968; (f) S. A. Weiner, *J. Amer. Chem. Soc.*, **93**, 425 (1971); (g) G. S. Hammond and S. A. Weiner, *Intra-Sci. Chem. Rep.*, **3**, 241 (1969).

(2) J. Dedinas and T. H. Regan, *J. Phys. Chem.*, **76**, 3926 (1972).

(3) Phosphorescence spectrum reported by J. Simpson and J. Offen, *J. Chem. Phys.*, **55**, 4832 (1971).

(4) (a) A. Singh, M. G. Jonasson, F. C. Sopchyshyn, and F. P. Sargent, XXXIIIrd International Congress of Pure and Applied Chemistry, Boston, Mass., July 25–30, 1971, reported the identification of the ketyl radical generated by flash photolysis of **1** in 2-propanol. (b) The esr spectrum of the decafluorobenzophenone ketyl radical has been reported by F. P. Sargent and M. G. Bailey, *Can. J. Chem.*, **49**, 2350 (1971).

(5) N. Filipescu, J. P. Pinion, and F. L. Minn, *Chem. Commun.*, 1413 (1970).

(6) Surprisingly, there was no photoreduction of **1** in the presence of decafluorobenzhydrol. Aromatic ketones in the $^3(n_1\pi^*)$ state usually react with the corresponding alcohols:[1g] W. M. Moore, G. S. Hammond, and R. P. Foss, *J. Amer. Chem. Soc.*, **83**, 2789 (1961).

(7) N. C. Yang and S. Murov, *J. Amer. Chem. Soc.*, **88**, 2852 (1966).

(8) Estimates based on triplet lifetime,[1f,2] radical rate constants,[1f] and quenching by ground-state benzophenone, $k_q = 1.2 \pm 0.2 \times 10^8$ M^{-1} sec^{-1},[9a] indicate that at 0.1 *M* concentration used by Yang and Murov,[7] the latter type of quenching was more probable than quenching by radicals.

(9) (a) M. B. Ledger and G. Porter, *J. Chem. Soc., Faraday Trans. 1*, **68**, 539 (1972); (b) S. A. Weiner, *J. Amer. Chem. Soc.*, **93**, 6978 (1971).

(8) K. Bowden, I. M. Heilbron, E. R. H. Jones, and B. C. L. Weedon, *J. Chem. Soc.*, 39 (1946).

(9) A. C. Darby, H. B. Henbest, and I. McClenaghan, *Chem. Ind. (London)*, 462 (1962); H. B. Henbest, *Proc. Chem. Soc.*, 159 (1963); R. Zurflüh, E. N. Wall, J. B. Siddall, and J. A. Edwards, *J. Amer. Chem. Soc.*, **90**, 6224 (1968).

Table I. Solvent Effect in the Photoreduction of Decafluorobenzophenone

	Solvent		
	Perfluoromethylcyclohexane		2-Propanol
Concn, 2-propanol (*M*)	0.01	0.02	13.6
Concn, $(C_6F_5)_2CO$ (*M*)	0.01	0.02	0.01
I_a, einstein $l.^{-1}$ sec^{-1}	4.3×10^{-5}	2.5×10^{-5}	1×10^{-5}
Φ, $-(C_6F_5)_2CO$	1.16	1.37	0.62
Φ, $[(C_6F_5)_2COH]_2$	0.56	0.66	0.0
Φ, $(C_6H_5)_2CH(OH)$	0.05	0.06	0.60

2-propanol is used as a solvent, was obtained in low yields. Compound **2** gradually crystallized out from solution after irradiation. Identification of **2** was based on melting point (decomposes at 140°), mass spectroscopic, ir, uv, and elemental analysis. Mass spectrum peaks (0.001%) at *m/e* 708 and 707 correspond to $M^+ - H_2O$ and $M^+ - F$, respectively. The ir spectrum had a peak at 3620 cm^{-1} and a broad peak at 3240 cm^{-1}; both were assigned to hydroxyl protons. *Anal.* Calcd for $C_{26}H_2F_{20}O_2$: C, 43.0; H, 0.28. Found: C, 42.4; H, <1.0.

Compound **2** decomposes in 2-propanol to **1** and **3**. The rate of decomposition is negligible in perfluoroalkane containing 2-propanol at a concentration $\leqslant 0.02$ *M*. The decomposition of **2** is rapid in alcohols, slow in diethyl ether, and very slow in hydrocarbons. Figure 1 shows the uv absorption spectrum of **2** in cyclohexane and immediately after addition of a small amount of ethanol. These results indicate reversibility in the formation of **2** and show that in polar solvents, ketyl radicals of **1** disproportionate rather than recombine. This unusual reactivity is attributed to the inductive effect of the perfluorinated phenyl group, since benzophenone ketyl radicals as well as mono- and dihalo-substituted ones in polar solvents (ethanol–water, 2-propanol) at room temperature undergo radical recombination.[1g,9] Hydrogen bonding between the ketyl radicals and the solvent must be the main cause of the large changes in reactivity. The following mechanism (eq 1–5) is proposed on the basis

$$(C_6F_5)_2CO \xrightarrow{h\nu} {}^1(C_6F_5)_2CO \longrightarrow {}^3(C_6F_5)_2CO \quad (1)$$

$${}^3(C_6F_5)_2CO + (CH_3)_2CH(OH) \longrightarrow (C_6F_5)_2\dot{C}OH + (CH_3)_2\dot{C}OH \quad (2)$$

$$2(C_6F_5)_2\dot{C}OH \rightleftharpoons (C_6F_5)_2COHCOH(C_6F_5)_2 \quad (3)$$

$$2(C_6F_5)_2\dot{C}OH \longrightarrow (C_6F_5)_2CH(OH) + (C_6F_5)_2CO \quad (4)$$

$$(C_6F_5)_2CO + (CH_3)_2\dot{C}OH \longrightarrow (C_6F_5)_2\dot{C}OH + (CH_3)_2CO \quad (5)$$

of product yields, solvent effect, and related studies.[1] Reactions 1 and 2 have been reported.[2,4] Reactions of the primary radicals in the solvent cage account for <10% and are not indicated in the proposed mechanism. In perfluoroalkane, ketyl radical termination occurs by reaction 3, and in 2-propanol, by reaction 4. That Φ is twice as high in perfluoroalkane as in 2-propanol is in agreement with this mechanism. Reaction 5 is indicated by the dependence of Φ on ketone concentration.

Because fluorine substitution should decrease ketyl radical coupling rates,[1g] it was of interest to obtain some information on radical concentration and rate constants. Since quenching of the triplet state by

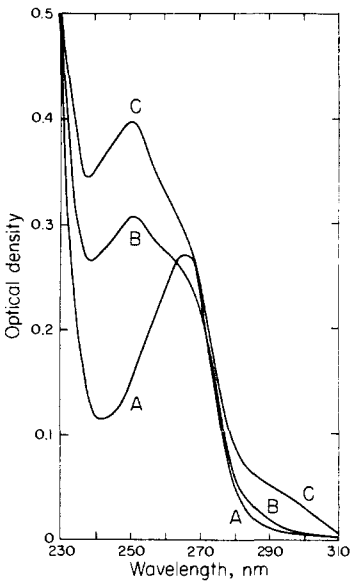

Figure 1. Decomposition of **2** in solution: (A) uv absorption spectrum of eicosafluorobenzopinacol in cyclohexane, 1×10^{-4} *M*, 1-cm cell; (B, C) spectra taken in succession immediately after addition of a small amount of ethanol to solution A.

radicals is nearly diffusion controlled,[10] $k_q \simeq 3 \times 10^9$ M^{-1} sec^{-1}; therefore, triplet quenching by radicals may occur at very high light intensity. The effect of I_a was investigated using light from a 1000-W mercury–xenon arc lamp filtered through 10 cm of water and Pyrex glass. The maximum I_a was 3×10^{-4} einstein $l.^{-1}$ sec^{-1}. Concentrations of both **1** and 2-propanol were 0.01 *M* in perfluoromethylcyclohexane (PMCH). There was no effect of I_a over an 18-fold variation. Therefore, triplet quenching by radicals was not occurring. In another experiment, using benzene as a quencher,[2] it was determined that $k_2 = 1.1 \times 10^8$ M^{-1} sec^{-1} in PMCH. From this and the maximum I_a used, the radical concentration in PMCH is found to be $<4 \times 10^{-5}$ *M* and $k_3 > 2 \times 10^5$ M^{-1} sec^{-1}. These values indicate high reactivity of decafluorobenzophenone ketyl radicals in perfluoroalkane solvent. Similarly, the I_a effect was not observed using 2-propanol solvent.

The lack of triplet quenching by radicals indicated that the interpretation of the I_a effect by Yang and Murov[7,11] may be incorrect. Thus, the effect of I_a was determined using a 0.01 *M* concentration of benzophenone in 2-propanol. Φ decreased by a factor of 3 for an 18-fold increase in I_a. In the benzophenone–cyclohexane system, using 0.05 *M* concentration, there was no effect of I_a on Φ. Therefore, triplet quenching by radicals was not occurring in cyclohexane. Comparison of the triplet lifetime[12] and the concentrations used in the two solvents indicate that there could not have been any triplet quenching by radicals in 2-propanol. The I_a effect in the benzophenone–2-propanol system may occur, however, because of light screening by the well-known yellow intermediate (YI),[1a] which has a

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(11) The work of Yang and Murov[7] has been referred to in several related studies: (a) S. G. Cohen and J. I. Cohen, *Tetrahedron Lett.*, 4823 (1968); (b) P. J. Wagner, *Mol. Photochem.*, **1**, 71 (1969); (c) B. M. Monroe and S. A. Weiner, *J. Amer. Chem. Soc.*, **91**, 450 (1969).

(12) G. Porter and M. R. Topp, *Proc. Roy. Soc., Ser. A*, **315**, 163 (1970).

high extinction coefficient.[13] YI is not formed either in the benzophenone–cyclohexane or in the decafluorobenzophenone–2-propanol system. The I_a effect is apparently related to the efficiency of energy transfer from YI to benzophenone. Triplet sensitization may be the mechanism of energy transfer since YI undergoes intersystem crossing[13] and has triplet energy similar to that of benzophenone.

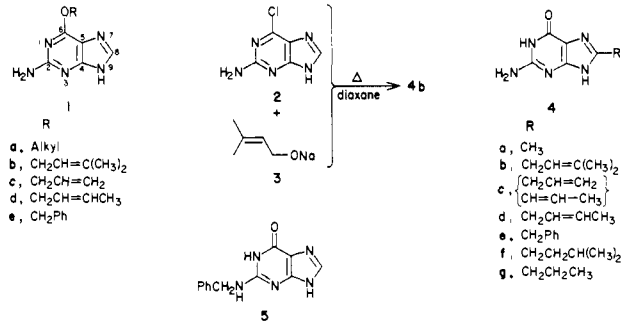
(13) N. Filipescu and F. L. Minn, *J. Amer. Chem. Soc.*, **90**, 1544 (1968).

Jonas Dedinas
Research Laboratories, Eastman Kodak Company
Rochester, New York 14650
Received May 21, 1973

Allylic Rearrangement from O^6 to C-8 in the Guanine Series

Sir:

Because of our interest in fluorescent derivatives of the nucleic acid bases[1-3] we sought to obtain a variety of O^6-substituted guanines (**1**), which are described as strongly fluorescent in the case of O^6-alkyl substituents.[4,5] When we attempted to extend the method of synthesis of O^6-alkylguanines (**1a**)[6] to the allylic and benzylic analogs, some unexpected products resulted. For example, when 2-amino-6-chloropurine (**2**) was caused to react with sodium 3-methyl-2-buten-1-oxide (**3**) (2 equiv) in dioxane at reflux (heterogeneous)



for 24 hr, none of the expected O^6-substituted guanine derivative could be detected. Instead, an isomeric product, $C_{10}H_{13}N_5O$, was isolated in 74% yield.[7] This product exhibited the following properties: (a) the nmr spectrum showed the presence of the 3-methyl-2-buten-1-yl side chain but the absence of an 8 proton; (b) no cleavage of the side chain resulted when the product was heated at 100° in 1 *N* HCl for 24 hr, indicating that it was not an O^6-substituted purine; (c) the mass spectrum showed maior peaks at *m/e* 219 $(M)^+$, 204 $(M - CH_3)^+$, 178 $(M - C_3H_5)^+$, 165 $(M - C_4H_6)^+$, and 140 $(M - C_6H_7)^+$, and no appreciable fragment ion of *m/e* 151 $(M - C_5H_8)^+$, indicating *C*-rather than *O*- or *N*-dimethylallyl substitution; (d) the uv spectrum showed $\lambda_{max}^{H_2O}$ (pH 1) 248 nm (ε 12,400), 276 (8210); (pH 7) 246 (9940), 278 (7420); (pH 13) 276 (9450), indicating an 8-substituted guanine, *e.g.*, **4a**.[8] The structure of the product of the reaction of **2** with **3** was established thereby as 8-(3-methyl-2-buten-1-yl)guanine (**4b**).[9] Corroboration of the assigned structure was obtained by catalytic reduction of **4b** to 8-(3-methylbut-1-yl)guanine (**4f**) and comparison with a sample of **4f**[9] obtained by unequivocal synthesis: condensation of 4-methylvaleryl chloride with 6-hydroxy-2,4,5-triaminopyrimidine, followed by ring closure of the sodium salt of the amide intermediate (55% overall yield).

The unusual reaction of **2** + **3** to produce **4b** obviously requires an initial displacement step that places the oxygen of the alkoxide **3** at the 6 position of the purine ring and subsequent allylic C–O bond cleavage. In the only previous example of an allylic rearrangement in the purine series the allyl group moved from an exocyclic oxygen to a neighboring ring nitrogen, specifically, 2,6-diallyloxy-7-methylpurine, when heated at 150°, to 1,3-diallyl-2,6-dioxo-7-methylpurine.[10] Rearrangement from an exocyclic oxygen to a ring carbon is unknown with purines, although two examples of a Claisen-type rearrangement from O to C have been reported with pyrimidines.[11-13] The only example of C-8 alkylation of 8-unsubstituted purines is the reaction of sodium theophyllinate with 2-butenyl bromide and benzyl chloride.[14] There is no precedent in the purine system for the observed rearrangement of the allylic side chain from O^6 to C-8. One formal intramolecular route for visualizing the overall result is a combined Claisen–Cope rearrangement *via* C-5 involving two [3*s*,3*s*] sigmatropic shifts.[15-17]

To answer the question of the generality of this rearrangement, we selected other examples representative of allyl, crotyl, alkyl, and benzyl substitution. Reaction of 2-amino-6-chloropurine (**2**) with sodium allyloxide (2–10 equiv) at reflux in either allyl alcohol (97°) or dioxane (101°) for 24 hr yielded O^6-allylguanine (**1c**),[9] with a characteristic uv spectrum for O^6-alkyl substitution: $\lambda_{max}^{H_2O}$ (pH 1) 230 nm (sh) (ε 6000), 285 (11,000); (pH 7) 239 (7900), 281 (8400); (pH 13) 245 (sh) (4900), 283 (8800). When a higher boiling solvent, *e.g.*, diglyme (150°), was used, the

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(7) The reported yields are of analytically pure samples. The crude yields in the displacement reactions were between 90 and 95%, and on thin layer chromatography on silica gel in three different solvent systems these showed uv-absorbing spots with R_f values corresponding to the products here reported; no other spots were observed.
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(9) The microanalytical data (C, H, N) obtained for all of the new compounds described herein were correct within acceptable limits (±0.30%) of those calculated according to the respective molecular formulas. Since, in general, the guanine derivatives decompose on heating and 8-substituted guanines melt at >300°, melting points do not offer meaningful criteria of purity in this series.
(10) E. Bergmann and H. Heimhold, *J. Chem. Soc.*, 1365 (1935).
(11) H. J. Minnemeyer, P. B. Clarke, and H. Tieckelmann, *J. Org. Chem.*, **31**, 406 (1966).
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(13) B. A. Otter, A. Taube, and J. J. Fox, *J. Org. Chem.*, **36**, 1251 (1971).
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(16) J. Borgulya, R. Madeja, P. Fahrni, H.-J. Hansen, H. Schmid, and R. Barner, *Helv. Chim. Acta*, **56**, 14 (1973).
(17) U. Widmer, J. Zsindely, H.-J. Hansen, and H. Schmid, *ibid.*, **56**, 75 (1973).