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THE PHOTO-REDUCTIONS OF β-KETOPHOSPHONATES IN ETHYL ETHER[1]

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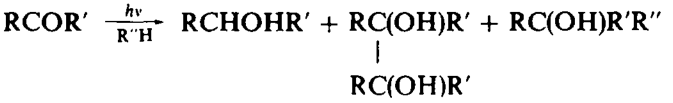
Abstract—The photo-reductions of dialkyl β-ketophosphonates and ethyl acetoacetate have been studied in detail. β-Ketophosphonates have been found to be photo-reduced efficiently to form corresponding β-hydroxyphosphonates, the quantum yields for disappearance of ketones being 0·6–0·7. By quenching experiments with piperylene, values for bimolecular hydrogen abstraction rate constants (k_r) by triplet β-keto esters have been estimated. High quantum yields and k_r values observed in β-ketophosphonates are discussed in terms of intramolecular heavy atom effect and electronic configuration of n–π* triplet states of ketones.

IT HAS been recognized that aliphatic ketones can undergo several distinct types of photo-reactions,[2] e.g. main photo-reactions of aliphatic ketones without γ-hydrogen in an appropriate hydrogen donating organic solvent are intermolecular reductions to give corresponding hydroxy compounds, together with the formation of pinacols and cross-coupled products of ketyl radicals with solvents.[3]



$$\mathrm{RCOR'} \xrightarrow[\mathrm{R''H}]{h\nu} \mathrm{RCHOHR'} + \underset{\displaystyle \mathrm{RC(OH)R'}}{\underset{|}{\mathrm{RC(OH)R'}}} + \mathrm{RC(OH)R'R''}$$

Although the quantitative studies of photo-reductions of aromatic ketones[2] have been reported, such studies on aliphatic ketones are few. We have studied the photo-reactions of β-ketophosphonates as an extension of the photo-reactions of organo-phosphorus compounds[4] and found that they are efficiently photo-reduced in ethyl ether to give monomeric β-hydroxyphosphonates. Although photo-reactions of ketones containing a heteroatom, e.g. silicone[5] and sulphur[6] have been reported, kinetic studies on these ketones are unavailable and in the present paper our discussions are based on kinetic experiments.

RESULTS AND DISCUSSION

Irradiation products. Irradiation of β-ketophosphonates (I) in ethyl ether gave after distillation corresponding β-hydroxyphosphonates (II) as the only isolated product in high yields (82–87%). Identification of the products were performed by

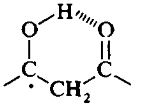
$$\mathrm{RCO\text{-}CH_2\text{-}P(O)(OR')_2} \xrightarrow[\text{ether}]{h\nu} \mathrm{RCH(OH)\text{-}CH_2\text{-}P(O)(OR')_2}$$

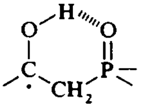
Ia: R = Me, R′ = Et
b: R = Et, R′ = Et
c: R = Et, R′ = i-Pr

IIa: R = Me, R′ = Et
b: R = Et, R′ = Et
c: R = Et, R′ = i-Pr

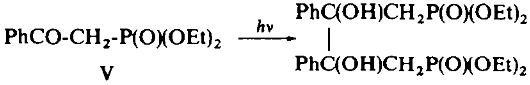
GLC and IR spectroscopy. GLC analysis of the irradiation mixture shows exclusive formation of II, but no other expected products such as pinacols, cross-coupled products and the products derived from Norrish type I cleavage, could be detected, although type I cleavage to give aldehydes or ketones has been reported to be an important process in the photolysis of α-keto esters.[7] Furthermore, no intramolecular δ-hydrogen abstraction seems to occur even in the reaction of Ic, which has a tertiary hydrogen atom in δ-position, although it is possible in the photochemical ring closure of 4-methyl-4-methoxy-2-pentanone to form a hydroxyfuran derivative.[8] In the present reactions, these reactions did not occur even in the irradiation in benzene, which is a poor hydrogen donor. Similar irradiation of ethyl acetoacetate, β-keto ester of carbon analog, in ethyl ether also gave corresponding β-hydroxy ester (70%) as a main product together with two GLC peaks, attributed to pinacol and cross-coupled product, yields of which are estimated to be smaller than 10% by GLC. The cross-coupling of ketyl radicals with ethyl ether in the photo-reactions of ketones in ethyl ether is known[9] to give hydroxy ethers. In this case again type I cleavage was not observed.

Thus a main product in this photo-reduction is β-hydroxy ester and this reduction may be a convenient method for the preparation of β-hydroxyphosphonates, which are difficult to prepare.[10] This fact is in marked contrast to the photoreductions of α-dicarbonyl compounds[11, 12] in which main products are pinacols or cross-coupled products. This is explained by assuming that ketyl radicals derived from β-keto esters have no resonance form and are less stabilized than α-dicarbonyl compounds, in which the delocalization of an odd electron to an adjacent carbonyl group may stabilize the intermediate ketyl radicals. However, the formation of pinacol and cross-coupled products, in small amounts from ethyl acetoacetate in spite of the exclusive formation of II from I may be due to the difference in steric hindrance of ketyl radicals (III and IV), in which hydrogen bonding may occur.


III


IV

Phenacylphosphonate (V), the ketal radical of which is more resonance-stabilized, gave after irradiation pinacol (VI)



$$\underset{\mathrm{V}}{\mathrm{PhCO\text{-}CH_2\text{-}P(O)(OEt)_2}} \xrightarrow{h\nu} \begin{array}{l} \mathrm{PhC(OH)CH_2P(O)(OEt)_2} \\ \quad | \\ \mathrm{PhC(OH)CH_2P(O)(OEt)_2} \end{array}$$

VI

as a sole product similar to the photo-reductions of other simple aromatic ketones.

Quantum yields and quenching studies. The quantum yields for the disappearance of ketones are listed in Table 1. On addition of piperylene (1,3-pentadiene), which is known to accept efficiently triplet energy from ketones,[13] the photo-reduction is greatly suppressed, suggesting the reaction proceeds via a triplet state as established in the general photo-reductions of simple ketones. The variation of quantum yields

(ϕ) with quencher concentration $[Q]$ should follow Eq. 5, if kinetically significant pathways of the reduction are assumed to be Eqs 2–4.

$$\mathrm{RCOR'(S_0)} \xrightarrow{h\nu} \mathrm{RCOR'}(S_m) \rightarrow \mathrm{RCOR'}(S_1) \xrightarrow{k_{ic}} \mathrm{RCOR'}(T_m) \rightarrow \mathrm{RCOR'}(T_1) \tag{1}$$

$$\mathrm{RCOR'}(T_1) \xrightarrow{k_d} \mathrm{RCOR'}(S_0) \tag{2}$$

$$\mathrm{RCOR'}(T_1) + Q \xrightarrow{k_q} \mathrm{RCOR'}(S_0) + Q^* \tag{3}$$

$$\mathrm{RCOR'}(T_1) + \mathrm{R''H} \xrightarrow{k_r} \mathrm{R\dot{C}(OH)R'} + \cdot\mathrm{R''} \tag{4}$$

$$\phi = ak_r[\mathrm{R''H}]/\{k_r[\mathrm{R''H}] + k_d + k_q[Q]\} \tag{5a}$$

or

$$\frac{1}{\phi} = \frac{1}{a} + \frac{k_d}{aK_r[\mathrm{R''H}]} + \frac{k_q[Q]}{ak_r[\mathrm{R''H}]} \tag{5b}$$

a: efficiency of conversion of initially excited singlet state of ketones to the triplet.

Fig. 1 shows the plot of reciprocal quantum yield ($1/\phi$) vs. quencher concentration $[Q]$ for Ia and ethyl acetoacetate. Since $1/\phi$ was not measured as a function of ethyl

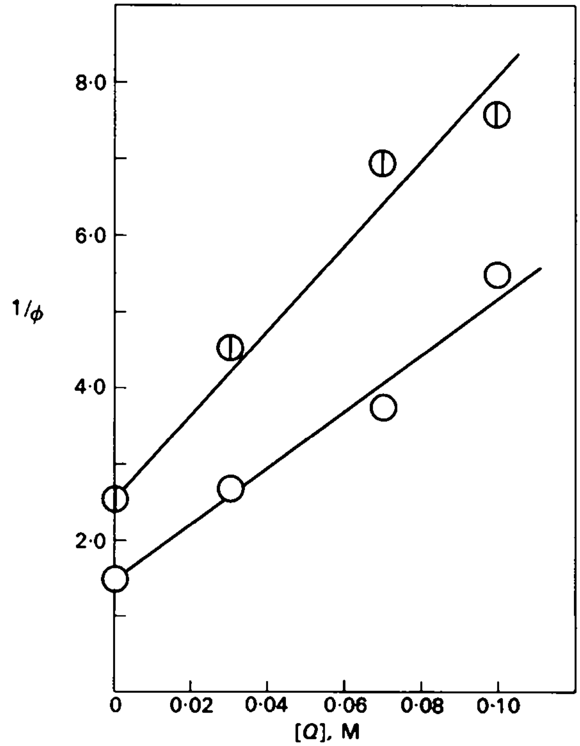


FIG. 1 Photoreductions of diethyl acetonylphosphonate (–○–) and ethyl acetoacetate (–⦶–) in ethyl ether. Variation of reciprocal quantum yield ($1/\phi$) with quencher concentration $[Q]$.

ether, a could not be determined. However, the value was taken as unity for the purpose of calculation, because k_{ic} is large and a is close to unity in ordinary ketones. From the slopes of lines in Fig. 1, the value of k_q/k_r at constant (neat) reductant can be estimated. Assuming that quenching of triplet is diffusion-controlled, the value of k_r, a measure of the inherent reactivity of triplet states of ketones, may be estimated. Hence, assuming again the bimolecular diffusion-controlled rate constant for neat ethyl ether at 20° to be $2{\cdot}8 \times 10^{10}\ M^{-1} \cdot sec^{-1}$ on the basis of Debye relation,[14] we can obtain k_r for β-keto esters. These values are listed in Table 1 together with the values by previous authors[15-17] for other ketones. Examination of Table 1 shows that high quantum yield and high reactivity of triplet state (k_r) are characteristic for the reductions of ketophosphonates.

TABLE 1. QUATUM YIELDS AND ESTIMATED RATE CONSTANTS OF VARIOUS KETONES

Ketones	ϕ [−ketone]	k_q/k_r	$k_r \times 10^{-6}\ M^{-1}.sec^{-1}$
$CH_3COCH_2P(O)(OEt)_2$	0·66	3340	6·83
CH_3COCH_2COOEt	0·39	4920	4·63
$CH_3COCOOH$[a]	0·79	612	5·23
$CH_3COCOOH$[b]	0·44	5700	2·3
Ph_2CO[c]	0·8–2·0	—	1·28
Ph_2CO[d]	0·34	—	—

[a] in i-PrOH.[15]
[b] in t-BuOH.[15]
[c] in i-PrOH.[16]
[d] in n-octyl methyl ether.[17]

This observed high values of ϕ and k_r may be accounted for as follows.

(1) The spin-orbital coupling may be increased by the presence of a P atom and thus k_{ic} is expected to be larger than other ketones. The increase in spin-orbital coupling by the presence of a P atom is anticipated from the comparison of life times of phosphorescence, τ_p, 5·4 for triphenylmethane and $1{\cdot}4 \times 10^{-2}$ sec for triphenylphosphine.[18] The high value of k_{ic} was also expected in the type II reactions of deuterated ketones.[19]

(2) Reactive specie for the photo-reductions have been considered to be n–π* triplet state of ketones, in which the carbonyl O atom is more positively charged than that of the ground state.[2a] Hence, the reactivity of this state may be suppressed by the presence of an electron-releasing group or a conjugated system by reducing the positive character of carbonyl oxygen,[2a] while it is increased by the presence of electron-attracting groups, such as —P(O)(OR)$_2$ and —COOR at β-position to carbonyl group in this reaction. Therefore, k_r values should be higher than those for other aromatic ketones. Rather low quantum yield for ethyl acetoacetate, in spite of having high k_r value, may be due to a small k_{ic} value.

(3) Reversibility of hydrogen abstraction, e.g.

$$RCOR'(T_1) + R''H \rightarrow R\dot{C}(OH)R' + \cdot R''$$

$$R\dot{C}(OH)R' + \cdot R'' \rightarrow RCOR'(S_0) + R''H$$

may also reduce the over-all quantum yield[2a] and such a reaction has been reported for the photo-reduction in ether.[17] However, the presence of proton accepter (C=O or P=O group) may stabilize the intermediate ketyl radical by intramolecular hydrogen bonding (III and IV) and thus reduce the reversible nature.

The photochemical reactions of ketophosphonates with γ-hydrogen are currently being investigated in our laboratory.

EXPERIMENTAL

GLC was carried out by employing a Yanagimoto Model GCG-500F with a flame ionization detector using following columns and conditions; (A) a 2m × 3mm column of 10% silicone SE-30 on 40–60 mesh Fluoropack 80 at 150°, He (25 ml/min); (B) a 2m × 3 mm column of 5% PEG 20M on 60–80 mesh Celite CS at 120°, He (25 ml/min). The IR spectra were measured by a Perkin–Elmer Model 337 grating spectrophotometer.

Materials. Dialkyl β-ketophosphonates (Ia–c and V) were prepared by the reactions of corresponding α-bromoketones with trialkyl phosphites[20] and they were purified by duplicate rectifications. Ethyl acetoacetate was distilled commercial material. Purities of these compounds were assessed by GLC, where a single peak was observed for each ketones. Ethyl ether and piperylene were used without further purification.

Authentic β-hydroxyphosphonates (II) were prepared[21] by the acid-catalysed hydrolysis of β-acetoxyphosphonates, obtained[21] by the Arbuzov reactions of corresponding α-bromoacetoxy derivatives with trialkyl phosphites.

Ac_2O and pyridine were distilled before use.

Irradiation of I in ethyl ether

(a) *Procedure and analysis of products.* A soln of Ia (6·0 g) in ethyl ether (300 ml) was irradiated in an immersion type reaction vessel using Holas 300 W high press Hg lamp for 6 hr at 20–23°. After irradiation, the solvent was carefully evaporated under reduced press. By distillation of residual yellow liquid (6·2 g), the following fractions were collected; (i) b.p. 155–156°/22–23 mm (5·3 g); (ii) b.p. 160–161°/22–23 mm (0·5 g) and residual brownish viscous liquid (0·4 g). The comparison of GLC and IR spectrum with the authentic material identified fraction (i) as IIa and fraction (ii) as unreacted Ia. The yield of IIa was 87%. Similar procedure for Ib and c gave corresponding IIb and c in the yields of 82·5 and 85%, respectively. GLC analysis of the reaction mixture before evaporation of the solvent shows no peak attributable to the product derived from type I reaction, i.e. aldehydes and alkylphosphonates.

(b) *Quantum yields and quenching experiments.* A soln of 0·1 M in ethyl ether with or without a quencher, which was degassed and substituted with N_2, was placed in a colsed square quartz cell (1 × 1 × 4 cm). The reaction cell was irradiated at mainly 3130 Å using a filter system[22] consisting of $NiSO_4 \cdot 6H_2O$ (46 g) and $CoSO_4 \cdot 7H_2O$ (14 g) per 100 ml water, and Toshiba UV-27 filter. Light intensities were monitored by a ferrioxylate actinometer.[23] After irradiation, acetylation with Ac_2O and pyridine at 80° for 2·5 hr was conducted, because separation of peaks of ketones and reduction products are unsatisfactory under our GLC conditions and direct analysis gave rather erratic results. Preliminary experiments showed that hydroxyphosphonates have been almost quantitatively acetylated but β-ketophosphonates were unchanged. After acetylation, remaining starting material was estimated by GLC using a column and conditions A.

Irradiation of phenacylphosphonate (V)

A soln of V (7·9 g) in ethyl ether (300 ml) was irradiated for 6 hr. Evaporation of the solvent gave crystals, which on recrystallization twice from acetone gave VI, m.p. 190–192°. The product was identified by IR spectrum and elemental analysis. (Found: C, 56·17; H, 7·01. $C_{24}H_{36}O_8P_2$ requires: C, 56·47; H, 7·11%).

Irradiation of ethyl acetoacetate

An ethyl ether soln of 0·1M ethyl acetoacetate was irradiated for 5 hr. Analysis with GLC using authentic materials showed the formation of ethyl β-hydroxybutyrate (70%) as a main product, together with products having other two GLC peaks attributable to pinacol and cross-coupled product.

Quantum yield and quenching experiments were performed with the similar procedure as described in the previous section.

REFERENCES

[1] Contribution No 130.

[2] For comprehensive reviews: [a] N. J. Turro, *Molecular Photochemistry* p. 137. Benjamin, New York (1965);
[b] J. G. Calvert and J. N. Pittz, Jr., *Photochemistry* p. 365. Wiley, New York (1966);
[c] D. C. Neckers, *Mechanistic Organic Photochemistry* p. 163. Reinhold, New York (1967).

[3] N. C. Yang, *Reactivity of the Photoexcited Organic Molecule* p. 146. Interscience, New York (1967).

[4] H. Tomioka, Y. Izawa and Y. Ogata, *Tetrahedron* **24**, 5739 (1968).

[5] A. G. Brook and J. M. Duff, *J. Am. Chem. Soc.* **89**, 454 (1967).

[6] P. de Mayo, *Tetrahedron Letters* 37 (1967); S. Iwasaki and K. Schaffner, *Helv. Chim. Acta* **51**, 557 (1968); C. Ganter and J.-F. Moser, *Ibid.* **51**, 300 (1968).

[7] P. A. Leermakers, P. C. Warren and G. F. Vesley, *J. Am. Chem. Soc.* **86**, 1768 (1964).

[8] D. J. Coyle, R. V. Peterson and J. Heicklen, *Ibid.* **86**, 3850 (1964).

[9] J. Meinwald and R. A. Chapman, *Ibid.* **90**, 3218 (1968).

[10] For example, G. V. Chelintser and V. K. Kuskov, *Zh. Obshch. Khim.* **16**, 1481 (1946).

[11] P. W. Jolly and P. de Mayo, *Canad. J. Chem.* **42**, 170 (1964).

[12] P. A. Leermakers and G. F. Vesley, *J. Am. Chem. Soc.* **85**, 3776 (1963).

[13] G. S. Hammond, P. A. Leermakers and N. J. Turro, *Ibid.* **83**, 2396 (1961).

[14] P. Debye, *Trans. Electrochem. Soc.* **82**, 265 (1942).

[15] D. S. Kendall and P. A. Leermakers, *J. Am. Chem. Soc.* **88**, 2766 (1966).

[16] A. Beckett and G. Porter, *Trans. Faraday Soc.* **59**, 2051 (1963).

[17] S. G. Cohen and A. Aktipis, *Tetrahedron Letters* 579 (1965).

[18] D. S. MacClure, *J. Chem. Phys.* **17**, 905 (1949).

[19] D. R. Coulson and N. C. Yang, *J. Am. Chem. Soc.* **88**, 4511 (1966).

[20] N. Kreuzkamp and H. Kayser, *Chem. Ber.* **89**, 1614 (1965).

[21] B. Ackerman, T. A. Jordan and D. Swern, *J. Am. Chem. Soc.* **78**, 6025 (1956).

[22] P. J. Wagner and G. S. Hammond, *Ibid.* **88**, 1245 (1966).

[23] C. G. Hatchard and C. A. Parker, *Proc. Roy. Soc.* **A235**, 578 (1956).