1,2-Dioxetane Intermediates in the Base Catalyzed Decomposition of α-Hydroperoxy Ketones
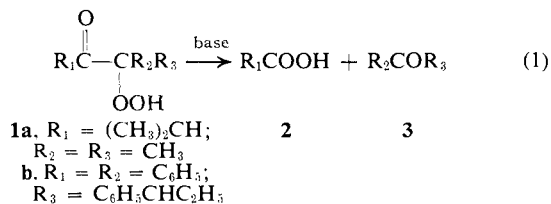
W. H. Richardson,* V. F. Hodge, D. L. Stiggall,
M. B. Yelvington, and F. C. Montgomery

*Contribution from the Department of Chemistry, San Diego State University,
San Diego, California 92115. Received February 21, 1974*

Abstract: A kinetic and product study of the base catalyzed decomposition of 2,4-dimethyl-2-hydroperoxy-3-pentanone (**1a**) and 2,3-diphenyl-2-hydroperoxyvalerophenone (**1b**) revealed that the reactions proceeded largely through 1,2-dioxetane intermediates. In competition with this cyclic path, a portion of the reaction was shown to proceed through an acyclic route with **1a**. It is proposed that excited state carbonyl production and chemiluminescence are associated with the cyclic path. From kinetic measurements based on light emission, the rate coefficients for the formation and decomposition of the 1,2-dioxetane intermediates were obtained. Kinetic data for decomposition of the cyclic peroxides as a function of base concentration indicated the presence of two 1,2-dioxetane intermediates with **1a**, namely, a hydroxy-1,2-dioxetane and its alkoxide anion. The rate of disappearance of the α-hydroperoxy ketones, as measured by light emission or by iodometric titration, is the same which indicates no buildup of the dioxetane intermediates during the reaction. Based on the formation of methyl isobutyrate from **1a** in the basic methanolic solutions, an assessment is made of the relative importance of the cyclic vs. the acyclic decomposition routes.

There are numerous proposals that α-hydroperoxy ketones are intermediates in the autooxidation of ketones.[1,2] In some instances, the hydroperoxides can be isolated either under basic or neutral reaction conditions. α-Hydroperoxy ketones produced *in situ* or isolated, undergo basic decomposition to yield an acid and a carbonyl compound (*cf.* eq 1).[3,4] Furthermore,

$$\underset{\substack{\text{OOH}}}{\overset{\text{O}}{\text{R}_1\text{C}-\text{CR}_2\text{R}_3}} \xrightarrow{\text{base}} \text{R}_1\text{COOH} + \text{R}_2\text{COR}_3 \qquad (1)$$

1a, $R_1 = (CH_3)_2CH$; **2** **3**
   $R_2 = R_3 = CH_3$
b. $R_1 = R_2 = C_6H_5$;
   $R_3 = C_6H_5CHC_2H_5$

luminescence produced upon heating α-hydroperoxy ketones has been known for a number of years.[1c] The cleavage products and the luminescence can be

conveniently explained by the intervention of a 1,2-dioxetane intermediate (**4**). Previous studies with iso-

$$\underset{\substack{\text{O}-\text{O}}}{\overset{\text{OH}}{\text{R}_1-\text{C}-\text{CR}_2\text{R}_3}}$$

4
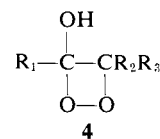
lated 1,2-dioxetanes show that these cyclic peroxides decompose to give carbonyl products, where a portion of these molecules are in an excited state.[5] However, alternative mechanisms for the basic decomposition of α-hydroperoxy ketones have been suggested which do not incorporate a 1,2-dioxetane intermediate.[1k,q,r]

The mechanism of the basic decomposition of α-hydroperoxy ketones is of particular interest to some bioluminescent reactions, where molecular oxygen is required.[6] Here, α-hydroperoxycarboxylic acid derivatives are proposed intermediates. It was originally suggested that these hydroperoxides cyclize with the carbonyl moiety to generate a 1,2-dioxetane.[6a] Subsequent decomposition of the 1,2-dioxetane would then give an excited state carbonyl species, which would show fluorescence. Indeed, dioxetanes of this type have been prepared and decompose to give excited state carbonyl products.[7] Recent oxygen-18 studies with firefly luciferin are, however, incompatible with a dioxetane intermediate (**5**) in this bioluminescent reaction.[6b,c] However, a similar study with *cypridina* luciferin indicates that bioluminescence occurs primarily through a dioxetane intermediate (**6**).[6d]

(1) (a) E. P. Kohler and R. P. Barnes, *J. Amer. Chem. Soc.*, **56**, 211 (1934); (b) E. P. Kohler and R. B. Thompson, *ibid.*, **59**, 887 (1937); (c) R. C. Fuson, D. J. Byers, and N. Rabjohn, *ibid.*, **63**, 2639 (1941); (d) R. C. Fuson, E. W. Maynert, and W. J. Shenk, Jr., *ibid.*, **67**, 1939 (1945); (e) R. C. Fuson and H. L. Jackson, *ibid.*, **72**, 1637 (1950); (f) W. v. E. Doering and J. D. Chanley, *ibid.*, **68**, 586 (1946); (g) W. v. E. Doering and R. M. Haines, *ibid.*, **76**, 482 (1954); (h) J. Rigaudy, *C. R. Acad. Sci.*, **226**, 1993 (1948); (i) D. B. Sharp, L. W. Patton, and S. F. Whitcomb, *J. Amer. Chem. Soc.*, **73**, 5600 (1951); (j) W. Pritzkow, *Chem. Ber.*, **88**, 572 (1955); (k) E. Elkik, *Bull. Soc. Chim. Fr.*, 933 (1959); (l) H. R. Gersmann, H. J. W. Nieuwenhuis, and A. F. Bickel, *Proc. Chem. Soc., London*, 279 (1962); (m) W. H. Richardson and R. F. Steed, *J. Org. Chem.*, **32**, 771 (1967); (n) R. C. P. Cubbon and C. Hewlett, *J. Chem. Soc. C*, 2978 (1968); (o) T. Koga and T. Hara, *Bull. Chem. Soc. Jap.*, **39**, 664 (1966); (p) R. H. Young, *Chem. Commun.*, 704 (1970); (q) F. G. Bordwell, R. C. Scamehorn, and A. C. Knipe, *J. Amer. Chem. Soc.*, **92**, 2172 (1970); (r) F. G. Bordwell and A. C. Knipe, *ibid.*, **93**, 3416 (1971); (s) J. Carnduff and D. G. Leppard, *Chem. Commun.*, 975 (1971); 829 (1967); (t) H. R. Gersmann and A. F. Bickel, *J. Chem. Soc. B*, 2230 (1971); (u) M. F. Ansell, I. S. Shephard, and B. C. L. Weedon, *J. Chem. Soc. C*, 1857 (1971); H. Hart, *Pure Appl. Chem.*, **33**, 247 (1973).

(2) In the older literature α-hydroperoxy ketones are sometimes shown as 1,2-dioxetanes. More recent evidence shows this to be incorrect.[1m]

(3) If R_2 or $R_3 = H$, a competing dehydration reaction can occur to yield the α-diketone.[1h]

(4) A methyl ester, rather than an acid, was reported in the autooxidation of 1-phenyl-2-indanone in the presence of methanolic sodium methoxide.[1h,r]

(5) *Cf.* W. H. Richardson, M. B. Yelvington, and H. E. O'Neal, *J. Amer. Chem. Soc.*, **94**, 1619 (1972), and references therein.

(6) (a) W. D. McElroy, H. H. Seliger, and E. H. White, *Photochem. Photobiol.*, **10**, 153 (1969); (b) W. D. McElroy and M. DeLuca, "Chemiluminescence and Bioluminescence," M. J. Cormier, D. M. Hercules, and J. Lee, Ed., Plenum Press, New York, N. Y., 1973, p 285; (c) M. DeLuca and M. E. Dempsey, *ibid.*, p 345; (d) O. Shimomura and F. H. Johnson, *ibid.*, p 337.

(7) (a) W. Adam and J.-C. Liu, *J. Amer. Chem. Soc.*, **94**, 2894 (1972); (b) W. Adam and H.-C. Steinmetzer, *Angew. Chem., Int. Ed. Engl.*, **11**, 540 (1972).

5   6, R₁ =

$R_2 = -CH(CH_3)CH_2CH_3$

$R_3 = -CH_2CH_2CH_2NHC \overset{NH}{\underset{NH_2}{\diagdown}}$
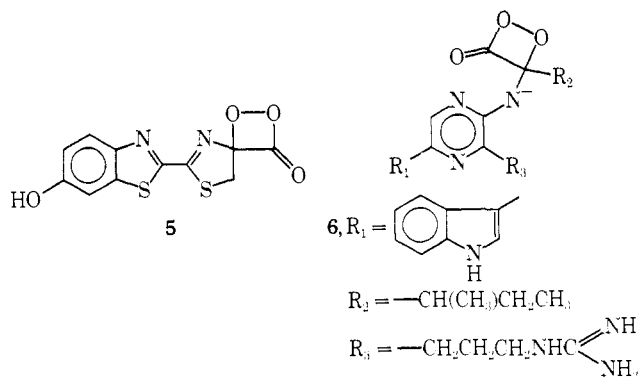
To avoid potential complications of the combined base catalyzed autooxidation of ketones followed by *in situ* decomposition of the α-dehydroperoxy ketone, we have isolated 1a and 1b and report the kinetics, products, and chemiluminescence of their base catalyzed reactions.

Results

Products. The major products from the basic decomposition of 2,4-dimethyl-2-hydroperoxy-3-pentanone (1a) in aqueous methanol are isobutyric acid and acetone according to the cleavage reaction (eq 1). The two major products are formed in approximately equivalent yields and there is no apparent effect of varying base concentration on the yields as seen from Table I. Methyl isobutyrate was a minor product and

Table I. Cleavage Products from the Basic Decomposition of 1a in 60% Aqueous Methanol at 30° [a]

		% yield[b]		
[NaOH], M	μ	CH_3-$COCH_3$	$(CH_3)_2$-$CHCOOH$	$(CH_3)_2$-$CHCOOCH_3$
0.100	1.6	81	84	1.3
0.250	1.6	79	79	
0.500	0.500	82	82	1.6

[a] With $[1a]_0 = 1.00 \times 10^{-2}$ M and 2 mol % Na₂EDTA, based on the sodium hydroxide concentration. [b] Based on 1.0 mol of product/mol of 1a.

its yield was not significantly altered by variation in base concentration. The reaction mixtures with 0.100 and 0.500 M base were checked for 2,4-dimethyl-2-hydroxy-3-pentanone, which is a product expected from the radical decomposition of 1a.[8] At the lower base concentration (0.100 M) the α-hydroxy ketone was not observed, while a 1.0% yield was found at the higher base concentration (0.500 M). The lack of a radical decomposition of 1a was also substantiated by the absence of oxygen[8] (2% yield detectability limit) from the reaction of 1a (1.00 × 10⁻² M) with 0.100 M base. With 1b (1.00 × 10⁻² M) and sodium hydroxide (0.500 M) in 16% acetone-84% methanol, 1,2-diphenyl-1-butanone (3b) and benzoic acid were obtained in 85 and 87% yields, respectively.

(8) Radical decomposition of hydroperoxides in the presence of base is reported to yield the corresponding alcohol and oxygen.[9] The reaction is suppressed by EDTA,[9a] suggesting metal ion catalysis.[10]
(9) (a) D. B. Denny and J. D. Rosen, *Tetrahedron*, 20, 271 (1964); (b) M. S. Karasch, A. Fono, W. Nudenberg, and B. Bischof, *J. Org. Chem.*, 17, 207 (1952); (c) V. A. Belyaev and M. S. Nemtsov, *J. Gen. Chem. USSR*, 31, 3594, 3599 (1961); 32, 3420 (1962).
(10) W. H. Richardson, *J. Amer. Chem. Soc.*, 87, 247 (1965).

Since methyl isobutyrate was observed in low yield from the basic decomposition of 1a in *aqueous* methanol, the reaction was carried out in anhydrous methanol to determine whether or not the ester was a major product, which underwent rapid hydrolysis in the aqueous medium. As seen from Table II, there is a significant increase in the yield of methyl isobutyrate in anhydrous methanol. Nonetheless, the major products are still acetone and isobutyric acid. A qualitative check did show that methyl isobutyrate undergoes rapid hydrolysis in 60% aqueous methanol with 0.100 M sodium hydroxide under the conditions of the product studies given in Table I. Although the yields of the α-hydroxy ketone are still low in anhydrous methanol, there is a small increase compared to aqueous methanol. This could be attributed to a lower concentration of EDTA in anhydrous methanol compared to aqueous methanol.[8]

Chemiluminescence. A characteristic reaction of 1,2-dioxetanes is the production of excited state carbonyl species, which may be evidenced by chemiluminescence.[7a,11] As a probe for 1,2-dioxetane intermediates in the basic decomposition of α-hydroperoxy ketones, qualitative chemiluminescence observations were made. When 1b was decomposed with 0.500 M sodium hydroxide in 16% acetone-84% methanol at 45°, blue-green light was emitted, which was easily visible in a dark room. Under similar conditions, but in 60% aqueous methanol solvent, light was not detected visually with 1a. However, light emission was visible in a dark room when fluorescein was added to the basic solution containing 1a.

Kinetics. Light emission from the decomposition of 1a in the presence of fluorescein allowed the kinetics of decomposition of 1a to be followed by this means. Upon mixing solutions of 1a and base containing fluorescein in aqueous methanol, light emission increases to a maximum and then decreases exponentially. This is analogous to light emission observations associated with the formation and decomposition of 3,3-dimethyl-1,2-dioxetane (7), which was produced from chloro-*tert*-butyl hydroperoxide (8) in basic aque-

$$\begin{array}{cc} \overset{O-O}{\underset{(CH_3)_2C-CH_2}{|\quad|}} & \overset{OOH}{\underset{(CH_3)_2CCH_2Cl}{|}} \\ 7 & 8 \end{array}$$

ous methanol.[11g] First-order kinetics for the decomposition of 1a were obtained from the exponential decay of light after the maximum was reached. Table III lists the rate coefficients obtained by light emission (k_E) and those obtained by iodometric titration (k_I) as a function of base concentration. From a graphical display of these data (Figure 1), it is seen that the k_E and k_I values are the same within experimental error. It is also apparent from Figure 1 that the reaction is not simply first order in base concentration. Instead, the decomposition of 1a increases rapidly with increasing base concentration and then the catalytic effect of base

(11) (a) K. R. Kopecky and C. Mumford, *Can. J. Chem.*, 47, 709 (1969); (b) P. D. Wildes and E. H. White, *J. Amer. Chem. Soc.*, 93, 6286 (1971); (c) S. Mazur and C. S. Foote, *ibid.*, 92, 3225 (1970); (d) T. Wilson and A. P. Schaap, *ibid.*, 93, 4126 (1971); (e) N. J. Turro and P. Lechtken, *ibid.*, 94, 2886 (1972); (f) J. H. Wieringa, J. Strating, H. Wynberg, and W. Adam, *Tetrahedron Lett.*, 169 (1972); (g) W. H. Richardson and V. F. Hodge, *ibid.*, 93, 3996 (1971); (h) W. H. Richardson, F. C. Montgomery, and M. B. Yelvington, *ibid.*, 94, 9277 (1972).

Table II. Products from the Decomposition of **1a** in Absolute Methanol with Sodium Methoxide at 30°

| | | | | | OH |
| | | | | | \| |
[NaOCH₃],[a] M	10²[1a]₀	CH₃COCH₃	(CH₃)₂CHCOOH	(CH₃)₂CHCOOCH₃	(CH₃)₂CCOCH(CH₃)₂
			─% yield[b]─		
0.050	1.07	87	72	28	
0.100	4.80	83	69	32	4.0
0.500	1.12	88	70	32	3.0

[a] With 2 mol % NaEDTA based on [NaOCH₃] added to the stock base solution. A portion of the Na₂EDTA did not dissolve in this medium. [b] Based on 1.0 mol of product/mol of **1a**.
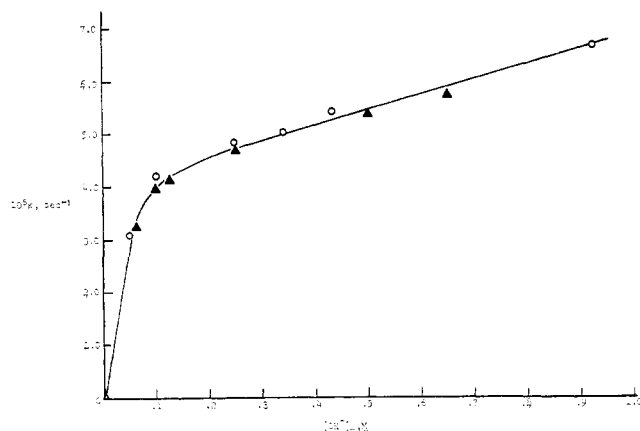

Figure 1. Observed rate coefficients for the decomposition of **1a** as measured iodometrically (k_I, O) and by light emission (k_E, ▲) as a function of base concentration in 60% aqueous methanol at 30°. The ionic strength is constant at 1.60 M and 2 mol % EDTA is present.

Table III. Effect of Base on the Rate of Decomposition of **1a** as Determined Iodometrically (k_I) and by Light Emission (k_E) in 60% Aqueous Methanol at 30°[a]

[OH⁻]ᴛ, M	10⁵k_I, sec⁻¹	10⁵k_E, sec⁻¹
0.0500	3.08	
0.0625		3.25
0.100	4.21	3.98
0.125		4.15
0.247	4.85	
0.250		4.70
0.340	5.04	
0.431	5.41	
0.500		5.39
0.650		5.75
0.925	6.66	

[a] [1a] = 0.0100 M, μ = 1.60 M, [fluorescein] = 0.008 M, 2 mol % EDTA based on [OH⁻]ᴛ, where the latter is the total base concentration. The ionic strength (μ) was maintained constant with sodium perchlorate.

is diminished. This is reminiscent of the basic decomposition of chloro-*tert*-butyl hydroperoxide, where the dependence on base was explained by a preequilibrium between the hydroperoxide and its anion.[11g]

To test for first-order dependence on **1a**, the initial concentration of **1a** was varied over a tenfold range at 0.500 M base concentration, with only a 1% increase in k_E. The data are given in Table IV.

A limited amount of kinetic data was obtained with **1b** in the presence of base. Insolubility of **1b** in 60% aqueous methanol necessitated a change in solvent to 16% acetone–84% methanol. The iodometric (k_I) and emission (k_E) rate coefficients for **1b** are similar as was found with **1a**. For comparison, a k_E value

Table IV. Effect of Varying Initial Concentration of **1a** on the First-Order Rate Coefficient (k_E) at 30.00° in 60% Aqueous Methanol[a]

10²[1a], M	10⁵k_E, sec⁻¹
0.500	5.53 ± 0.07
1.00	5.39 ± 0.13
2.00	5.46 ± 0.02
5.00	5.59 ± 0.10

[a] With [NaOH] = 0.500 and 2 mol % Na₂EDTA based on the sodium hydroxide concentration. With 0.008 M fluorescein and μ = 1.6 (with sodium perchlorate).

for **1a** was determined in 16% acetone–84% methanol, and the results for **1a** and **1b** are given in Table V.

Table V. First-Order Rate Coefficients for the Basic Decomposition of **1a** and **1b** in 16% Acetone–84% Methanol at 30.1°[a]

Hydroperoxide[b]	10⁵k_I, sec⁻¹	10⁵k_E, sec⁻¹
1b	121	116[c]
1a		3.68

[a] With 0.472 M sodium hydroxide, containing 2 mol % Na₂EDTA, based on the [OH⁻] concentration, and 0.008 M fluorescein. [b] 1.00 × 10⁻² M. [c] Identical rate coefficient without fluorescein.

It was possible to measure light emission from **1b** without added fluorescein. The k_E value was identical with that with 0.008 M fluorescein, which indicates that the acceptor is not altering the kinetics.

Light emission from **1b** and from **1a** with fluorescein, upon basic decomposition, is indicative of the generation of an excited state species. To show that light emission was not the result of an anomalous reaction involving simply the tertiary hydroperoxide group in **1a** and **1b**, a control experiment with 10⁻² M *tert*-butyl hydroperoxide in the presence of fluorescein under these basic conditions (1.58 M) was made. No detectable light emission was observed. An intermediate must then be generated from the basic decomposition of **1a** and **1b**, which is unique to the α-hydroperoxy ketone structural unit and is responsible for light emission. The formation and disappearance of this intermediate may be treated by consecutive first-order methods[12] with eq 2, where $\tau_{max} = k_E t_{max}$, $\kappa = k_{f(obsd)}/k_E$,

$$\tau_{max} = \frac{2.303 \log \kappa}{\kappa - 1} \tag{2}$$

and t_{max} is the time at maximum emission.[11g] By this treatment the rate coefficient for decomposition of the intermediate ($k_{f(obsd)}$) can be calculated by an itera-

(12) A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," Wiley, New York, N. Y., 1961, p 166.

tive process from values of t_{max} and k_E. These data and the results of the calculation are given in Table VI.

Table VI. Emission Rate Coefficients (k_E), Time at Maximum Emission (t_{max}), and Calculated Rate Coefficients for Decomposition of the Intermediate ($k_{f_{(obsd)}}$) as a Function of Base Concentration at 30.0° [a]

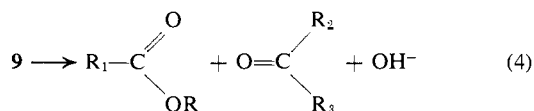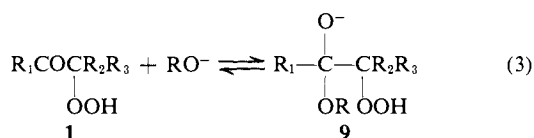| Hydro-peroxide	$[OH^-]_T$, M	$10^5 k_E$, sec^{-1}	t_{max}, sec	$10^2 k_{f_{(obsd)}}$, sec^{-1}
1a[b]	0.0625	3.25	15.7	62.7
1a[b]	0.125	4.15	25.0	34.4
1a[b]	0.250	4.70	44.7	18.6
1a[b]	0.500	5.39	66.7	11.5
1a[b]	0.650	5.75	90.2	8.05
1a[c]	0.472	3.68	204	3.35
1b[c]	0.472	116	36	13.3

[a] [Fluorescein] = 0.008 M and 2 mol % EDTA based on [NaOH]. [b] In 60% aqueous methanol and μ = 1.60. [c] In 16% acetone-84% methanol at 30.1°.
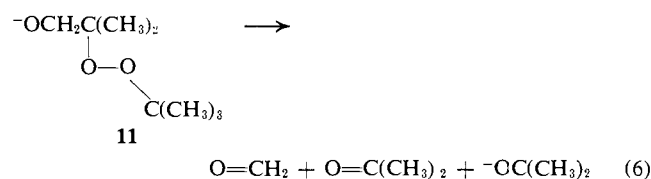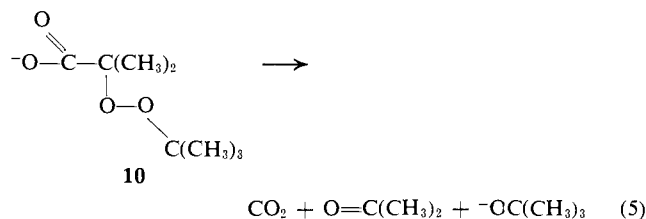
Discussion

Chemiluminescent Intermediates. The most likely candidate responsible for chemiluminescence is the 1,2-dioxetane, **4**. Previous reports[7a,11] show that 1,2-dioxetanes undergo decomposition to produce excited state carbonyl species, which may undergo fluorescence or transfer energy to an acceptor which shows fluorescence. The known mode of decomposition of 1,2-dioxetanes to give carbonyl products[5,7,11] is also consistent with the products observed from **1a** and **1b**.

Alternative explanations for chemiluminescence appear unlikely. The lack of light emission from *tert*-butyl hydroperoxide under basic conditions with fluorescein shows that anomalous reactions of *solely* the hydroperoxide group in **1a** and **1b** cannot explain light emission. A carbonyl group α to the hydroperoxide function is then a necessary requirement for chemiluminescence, an arrangement which can readily lead to 1,2-dioxetane, **4**. The possibility of light emission involving excited state carbonyl species produced by fragmentation of **9** is unlikely, where R = H or
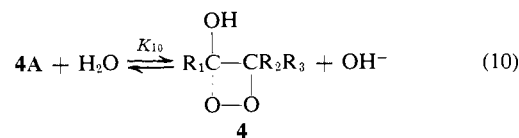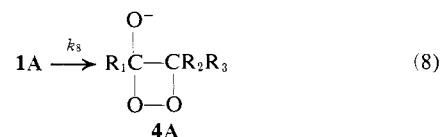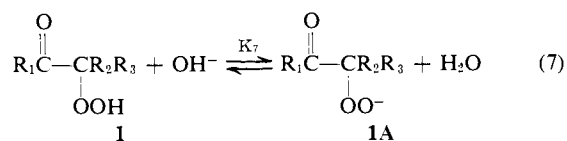
$$R_1COCR_2R_3 + RO^- \rightleftharpoons R_1 - \underset{\underset{\text{9}}{\overset{|}{\underset{OR}{\overset{|}{\underset{OOH}{}}}}}{\overset{O^-}{\overset{|}{C}}} - CR_2R_3 \quad (3)$$

$$\underset{\text{1}}{\underset{OOH}{}}$$

$$9 \longrightarrow R_1 - \overset{O}{\overset{\|}{C}} \diagdown_{OR} + O = C \diagup^{R_2} \diagdown_{R_3} + OH^- \quad (4)$$

CH_3. To date we have not found light emission (with an acceptor) from the analogous fragmentations of acyclic peroxides. Thus, the fragmentation of anions **10**[13] or **11**[14] did not produce detectable light emission in the presence of fluorescein. In agreement with these observations, thermochemical calculations indicate that there is insufficient energy available from eq 6 to reach the excited state manifold of either carbonyl species.[14] On the basis of the experimental observations and calculations with **10** and **11**, excited

$$\underset{\text{10}}{\overset{-O-\overset{O}{\overset{\|}{C}}-C(CH_3)_2}{\underset{\underset{C(CH_3)_3}{\overset{|}{O-O}}}{}}} \longrightarrow$$

$$CO_2 + O = C(CH_3)_2 + {}^-OC(CH_3)_3 \quad (5)$$

$$\underset{\text{11}}{\overset{-OCH_2C(CH_3)_2}{\underset{\underset{C(CH_3)_3}{\overset{|}{O-O}}}{}}} \longrightarrow$$

$$O = CH_2 + O = C(CH_3)_2 + {}^-OC(CH_3)_2 \quad (6)$$

state carbonyl production from the analogous peroxide **9** is improbable. However, inclusion of the ring strain energy ($\sim$25 kcal/mol) of a dioxetane intermediate (**4**) is sufficient to accommodate excited state carbonyl production.[15]

The rate coefficient $k_{f_{(obsd)}}$ in Table VI is then associated with the decomposition of a 1,2-dioxetane intermediate. The unique feature of $k_{f_{(obsd)}}$ is that its value decreases in a nonlinear manner with increasing base concentration (Figure 2). This observation can be accommodated by two 1,2-dioxetane intermediates as given in the mechanism below (eq 7-11), where the

$$R_1\overset{O}{\overset{\|}{C}} - \underset{\underset{\text{1}}{\overset{|}{OOH}}}{\overset{|}{C}}R_2R_3 + OH^- \overset{K_7}{\rightleftharpoons} R_1\overset{O}{\overset{\|}{C}} - \underset{\underset{\text{1A}}{\overset{|}{OO^-}}}{\overset{|}{C}}R_2R_3 + H_2O \quad (7)$$

$$1A \overset{k_8}{\longrightarrow} R_1\overset{O^-}{\overset{|}{\underset{\underset{\text{4A}}{\overset{|}{O-O}}}{C}}} - CR_2R_3 \quad (8)$$

$$4A \overset{k_9}{\longrightarrow} R_1COO^- + R_2COR_3 \quad (9)$$

$$4A + H_2O \overset{K_{10}}{\rightleftharpoons} R_1\overset{OH}{\overset{|}{\underset{\underset{\text{4}}{\overset{|}{O-O}}}{C}}} - CR_2R_3 + OH^- \quad (10)$$

$$4 \overset{k_{11}}{\longrightarrow} R_1COOH + R_2COR_3 \quad (11)$$

base is represented solely as hydroxide for convenience. Light emission results from the fluorescence of excited state species produced in eq 9 and 11 (**1b**) or from energy transfer from these species to an acceptor which undergoes fluorescence (**1a**). A steady state treatment for the rate of disappearance of the dioxetane intermediates **4** and **4A** yields eq 12, with the following approximations: $K_7[1] \ll 1$, $[4A] \ll ([OH^-] + [1A])$, $k_{-10}[OH^-]_T$

$$k_{f_{(obsd)}} = k_9 + \frac{k_{11}K_{10}}{[OH^-]_T} \quad (12)$$

$\gg k_{11}$, and $K_{10} \ll [OH^-]_T$, where $[OH^-]_T$ and $[OH^-]$ are the total base and specific hydroxide (or methoxide) concentrations, respectively. The first approximation can be numerically justified with the aid of a calculated value for K_7. The latter equilibrium constant is calculated to be 12.7 for **1a**

(13) W. H. Richardson, R. S. Smith, G. Snyder, B. Anderson, and G. L. Kranz, *J. Org. Chem.*, **37**, 3915 (1972).
(14) W. H. Richardson and T. C. Heesen, *ibid.*, **37**, 3416 (1972).
(15) H. E. O'Neal and W. H. Richardson, *J. Amer. Chem. Soc.*, **92**, 6553 (1970).
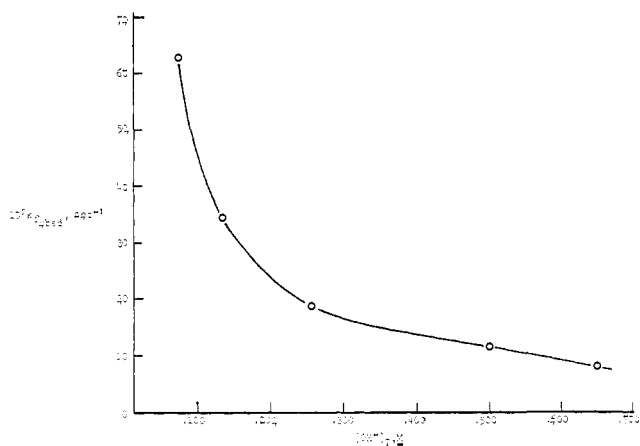
Figure 2. The observed rate coefficient for 1,2-dioxetane decomposition ($k_{f(obsd)}$) vs. base concentration with **1a** (1.00×10^{-2} M) in 60% aqueous methanol at 30°. The ionic strength (μ) is constant at 1.60 M and 2 mol % EDTA is present.

Figure 3. The observed rate coefficient for 1,2-dioxetane decomposition ($k_{f(obsd)}$) vs. the reciprocal of base concentration with **1a** (1.00×10^{-2} M) in 60% aqueous methanol at 30°. The ionic strength (μ) is constant at 1.60 M and 2 mol % EDTA is present.

from either a correlation of pK_a with σ^* or the chemical shift of the hydroperoxy proton in dimethyl sulfoxide.[16] The σ^* value for **1a** is estimated to be 0.400.[17] With $K_7 = 12.7$, the initial concentration of species **1** at 0.0625 M base, where the approximation is most stringent, is calculated to be 5.6×10^{-3} M with a total initial peroxide concentration of 10^{-2} M. Thus, $K_7[1] = 0.07$, which satisfies the approximation that $K_7[1] \ll 1$. Numerical justification of the remaining approximation is not possible, since the appropriate rate or equilibrium constants are unavailable. However, the latter three approximations appear reasonable. A plot of $k_{f(obsd)}$ vs. $1/[OH^-]_T$ for **1a** in 60% aqueous methanol is linear (Figure 3), which is in agreement with eq 12 and thus the proposed mechanism. From this plot, the intercept gives $k_9 = (3.52 \pm 0.11) \times 10^{-2}$ sec^{-1} and from the slope $k_{11}K_{10} = (3.73 \pm 0.01) \times 10^{-2}$ M sec^{-1} at 30°. In comparison, the rate coefficient for unimolecular decomposition of 3,3-dimethyl-1,2-dioxetane[11g] in 60% aqueous methanol at 30° is 1.3×10^{-3} sec^{-1}. This suggests that the dioxetane anion **4A** undergoes decomposition about 30-fold faster than the dialkyl peroxide. It should be noted that k_9 is obtained as the intercept from the plot and it is sensitive to the amount of cyclic vs. acyclic hydroperoxide decomposition (vide infra). We estimate that 30% acyclic decomposition could decrease k_9 by a factor of about 10-fold. Unfortunately it is not possible to obtain a value for the rate of decomposition of the hydroxy dioxetane (k_{11} in eq 11), since a value for K_{10} is unavailable. Rate coefficients for the decomposition of the dioxetane intermediates (k_9 and $k_{11}K_{10}$) are considerably larger than k_E or k_I for **1a** (cf. Table III). This is consistent with no appreciable buildup of dioxetane intermediates during the decomposition of **1a**, and thus yielding values of k_E and k_I that are essentially identical.[11g]

It is seen that the rate coefficients k_I and k_E, which measure the disappearance of **1a**, increase in a nonlinear manner with increasing base concentration. To support the portion of the mechanism given by eq 7

and 8, k_8 can be calculated at various base concentrations to determine its constancy. Values of k_8 are calculated from eq 13, which is derived in the same manner as for the basic decomposition of chloro-*tert*-butyl hydroperoxide.[11g] The value of K_7 is calculated to be 12.7 as described above, and the results are given in Table VII. Although there is some variation in

$$k_8 = \frac{k_E(1 + K_7[OH^-]_T)}{K_7[OH^-]_T} \tag{13}$$

Table VII. Calculated Values of k_8 for **1a** at Varying Base Concentrations in 60% Aqueous Methanol at 30°

$[OH^-]_T$, M	$10^5 k_E$, sec^{-1}	$10^5 k_8$,[a] sec^{-1}
0.0625	3.25	7.35
0.125	4.15	6.76
0.250	4.70	6.19
0.500	5.39	6.30
0.650	5.75	6.45
		Av 6.61 ± 0.36

[a] Calculated from eq 13.

k_8, calculated in this approximate manner, the average error is ±5%, which reasonably supports the prediction of a constant value of k_8 based on the proposed mechanism.

Cyclic vs. Acyclic Decomposition of 1. In the preceding sections, evidence was presented for 1,2-dioxetane intermediates, formed by a neighboring peroxide anion reaction with the α-carbonyl group. This is consistent with the recently reported[18] rate enhancement of about 10^4, compared to model compounds, that is found in the basic decomposition of α-hydroperoxy esters. However, a consideration of the product studies indicates that acyclic decomposition (eq 3 and 4) competes with the cyclic path (eq 7–11). In absolute methanol with sodium methoxide, isobutyric acid (after neutralization) is produced in about 70% yield from **1a**. This product is unique to the cyclic route, while methyl isobutyrate (ca. 30% yield) is

(16) W. H. Richardson and V. F. Hodge, *J. Org. Chem.*, **35**, 4012 (1970).

(17) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," Wiley, New York, N. Y., 1963, p 224.
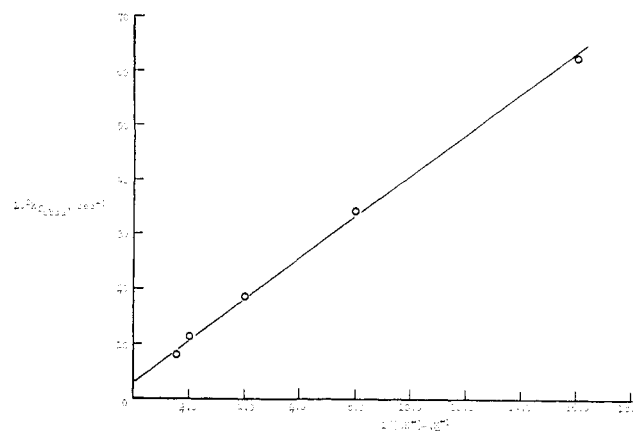
(18) F. McCapra, M. Roth, D. Hysert, and K. A. Zaklika, "Chemiluminescence and Bioluminescence," M. J. Cormier, D. M. Hercules, and J. Lee, Ed., Plenum Press, New York, N. Y., 1973, p 313.

characteristic of the acyclic path. In 60% aqueous methanol with base, the yield of methyl isobutyrate drops to 1–2%. This is a lower limit for the yield, since hydroxide can also produce isobutyric acid by the acyclic path and the ester is also hydrolyzed under the reaction conditions.

Conclusions

Kinetic data, products, and chemiluminescence observed with the basic decomposition of **1a** and **1b** are consistent with the reaction occurring predominantly through 1,2-dioxetane intermediates. The kinetic results indicate the presence of two dioxetane intermediates, **4** and **4A**. Formation of methyl isobutyrate from **1a** in absolute methanol with sodium methoxide shows that about 30% of the reaction proceeds by an acyclic path (eq 3 and 4), while the remaining 70% of the reaction occurs by the cyclic dioxetane route (eq 7–11).

Experimental Section[19]

Materials. Methanol (Matheson Coleman and Bell reagent) was purified by refluxing over magnesium turnings with a catalytic amount of iodine followed by distillation.[20] The 60% aqueous methanol (60% methanol–40% water) solvent was prepared as v/v per cent at 25° or by weight which corresponded to the volumes with purified methanol and doubly distilled water. The 16% acetone–84% methanol solvent was prepared as v/v per cent at 25° with purified methanol and anhydrous acetone (Matheson Coleman and Bell reagent dried over Drierite). The stock sodium hydroxide solution in 60% aqueous methanol was prepared from reagent grade pellets, starting with a 50% aqueous solution, which was filtered through a sintered glass frit to remove sodium carbonate. A 3 M sodium hydroxide solution in 60% aqueous methanol was prepared from the 50% aqueous solution by dilution with methanol and water. This solution was standardized with potassium acid phthalate (KHP) to a phenolphthalein end point. A stock 3.60 M sodium perchlorate (G. F. Smith Co.) solution in 60% aqueous methanol was prepared by first drying the salt in a vacuum oven at 100° (20 mm) overnight. The disodium salt of ethylenediaminetetraacetic acid (Matheson Coleman and Bell) was used as supplied. Sodium methoxide solutions in absolute methanol were prepared by adding sodium to purified methanol under nitrogen. These solutions were standardized with KHP as before.

Methyl Isobutyrate. Isobutyric acid (8.80 g, 0.100 mmol) and methanol (83.2 g, 2.60 mmol) were allowed to reflux for 3 hr over Amberlite resin IR-120(H+), which was previously treated with 2 M hydrochloric acid. The solution was removed from the resin, added to water, and extracted with ether. The ethereal extract was washed with water, dried over magnesium sulfate, and then distilled to give methyl isobutyrate (bp 92–93°, lit.[21] bp 92°) in 11% yield: nmr (CH₃)₂, 1.14, d (J = 7 Hz), 6.0; CH, 2.48, septet (J = 7 Hz), 1.0; and OCH₃, 3.62, s, 3.0.

2,4-Dimethyl-2-hydroperoxy-3-pentanone (1a). Autooxidation of diisopropyl ketone in monoglyme-*tert*-butyl alcohol with potassium *tert*-butoxide at −5° afforded **1a** in 30% yield, according to a previously reported procedure.[11] After two low temperature recrystallizations from *n*-pentane, white crystals (100% pure by iodometric titration[22]) were obtained, mp 43.5–44.5° (lit.[1n] 43–44°): nmr (CH₃)₂, 1.10, d (J = 7.1 Hz), 6; (CH₃)₂, 1.34, s, 6; CH, 3.33,

heptet (J = 7.1 Hz), 1; and OOH, 7.57, s, 1. The OOH absorption in dimethyl sulfoxide was at 11.60 ppm.

2,4-Dimethyl-2-hydroxy-3-pentanone. **1a** was reduced by sodium sulfite in aqueous methanol to give the alcohol in 72% yield by a previously reported method[1n]: nmr (CH₃)₂, 1.05, d (J = 6.7 Hz), 6.1; (CH₃)₂, 1.30, s, 6.1; CH, 3.05, heptet (J = 6.7 Hz), 1.0; and OH, 3.48, s, 1.0.

2,3-Diphenyl-2-hydroperoxyvalerophenone (1b). Autooxidation of 2,3-diphenylvalerophenone gave **1b** in 18% yield according to the general procedure of Kohler[23] as previously reported.[1m] Recrystallization from chloroform–*n*-pentane gave white needles (100% pure by iodometric titration[22]), mp 154.0–154.5° dec (lit.[1m] 152–153°). For the iodometric analysis about 10 mg of **1a** was dissolved in 10 ml of *tert*-butyl alcohol.

Product Studies. Solutions of **1a** and sodium hydroxide in 60% aqueous methanol were pipetted into a flask which was swept with nitrogen and stoppered. The solution was heated at 30° in a thermostated bath for approximately ten half-lives. An internal standard (cyclopentanone or *tert*-amyl alcohol) was weighed into the reaction mixture. Potassium iodide-starch paper gave a negative peroxide test at this time. Glc analyses were carried out on three different columns in comparison to an authentic mixture of the components including the internal standard: Porapak Q (Waters Associates, Inc.), 5 ft × ¹/₈ in., column (c) 110°; injector (i) 160°, detector (d) 180°, nitrogen flow 28 ml/min; retention times (t_r, min), methanol (3.0), acetone (13.9), methyl isobutyrate (35.2), and cyclopentanone (49.2); 15% diisododecyl phthalate on Varaport-30, 5 ft × ¹/₈ in., c 95°, i 130°, d 170°, nitrogen flow 28 ml/min (t_r, min), methanol (1.2), acetone (2.0), methyl isobutyrate (4.3), cyclopentanone (12.0), isobutyric acid (15.0), 2,4-dimethyl-2-hydroxy-3-pentanone (30); PAR 1 (Hewlett Packard), 2 ft × ¹/₈ in., c 120°, i 160°, d 230°, nitrogen flow 25 ml/min (t_r, min), acetone (5.7) and *tert*-amyl alcohol (31.2) and with c 90°, i 110°, d 200° (t_r, min), isobutyric acid (2.8) and *tert*-amyl alcohol (5.3). Analyses were first performed on the basic solutions and then the solutions were neutralized with 6 N hydrochloric acid to obtain analyses for isobutyric acid. Similar procedures were used for absolute methanol solutions. Gas analyses were performed by degassing solutions of **1a** and sodium hydroxide in 60% aqueous methanol, contained in separate arms of a two-armed vessel with a vacuum stopcock, three times to 10⁻⁴ mm. After degassing, the solutions were mixed in the vessel and heated at 30° for approximately ten half-lives. Gas analyses were performed on a vacuum line with Töppler pumping in the standard manner. No gas was detected within an error of 2% yield of oxygen, based on **1a**.

A sample of **1b** (34.6 mg, 0.100 mmol) was allowed to react with 10 ml of 0.500 M sodium hydroxide in 16% acetone–84% methanol under nitrogen in a stoppered vessel at 30° for approximately ten half-lives. After this time the solution gave a negative peroxide test with potassium iodide-starch paper. The solvent was removed by rotevaporation to give a solid which was triturated with three 3-ml portions of acetone. Rotevaporation of the solvent gave 19.0 mg (85% yield) of α-phenylbutyrophenone as a white solid, mp 55.5–56.5° (lit.[1g] mp 56–57°). The remaining salt from the trituration was dissolved in 1 ml of water and acidified with 6 N hydrochloric acid. The water was rotevaporated and the remaining solid was triturated with three 3-ml portions of acetone. Rotevaporation of acetone left 10.4 mg (87% yield) of benzoic acid as a white solid, mp 121.5–122.5° (lit.[24] mp 122.4°).

Kinetic Methods. Iodometric methods to obtain k_I were previously described.[1g,22] Some of the kinetic measurements to obtain k_E, from decay of light emission, were obtained as previously described.[1g] To obtain the t_{max} (time at maximum emission) values, a stopped-flow apparatus[25] was fabricated to fit a Beckman DU spectrophotometer, equipped with a 1P28 photomultiplier tube and a recorder. Solutions of the hydroperoxides and base with fluorescein were thermally equilibrated separately and then mixed.

(19) Melting points are corrected, while boiling points are uncorrected. Nuclear magnetic resonance (nmr) and infrared (ir) spectra were measured in 10% wt/vol carbon tetrachloride solution, unless specified otherwise. Nmr spectra were measured with a Varian A-60 spectrometer and chemical shifts are reported on the δ scale as (δ, coupling, area). Ir spectra were obtained with a Perkin-Elmer 337 or 621 spectrometer. Gas–liquid chromotography (glc) was performed with a Varian-Aerograph Hy-FI-III(FID) instrument.

(20) L. F. Fieser, "Experiments in Organic Chemistry," D. C. Heath, New York, N. Y., 1941, p 359.

(21) R. C. Weast, Ed., "Handbook of Chemistry and Physics," The Chemical Rubber Co., Cleveland, Ohio, 1967, p C-501.

(22) W. H. Richardson, *J. Amer. Chem. Soc.*, **87**, 247 (1965).

(23) E. P. Kohler, *Amer. Chem. J.*, **36**, 177, 529 (1906).

(24) Reference 21, p C-180.

(25) The plans for the stopped-flow apparatus were kindly furnished by Professor F. F. Freeman, Department of Chemistry, University of California, Irvine, California. The apparatus was built by Mr. Brian Funk and Mr. Evan Grant at CSUSD.