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THE UNIVERSITY OF ALBERTA

STUDIES ON 1,2-DIOXETANES

by

CEDRIC MUMFORD

Ⓒ

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled

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submitted by Cedric Mumford, in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

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TO MY MOTHER AND FATHER

ABSTRACT

A number of β-bromohydroperoxides have been prepared by the reaction between olefins, 1,3-dibromo-5,5-dimethylhydantoin, and hydrogen peroxide.

While the β-bromohydroperoxides of tetrasubstituted olefins react with base to give allylic hydroperoxides, those of lesser-substituted olefins react via the initial formation of four-membered cyclic peroxides. Starting with 2-methyl-2-butene it has been possible to prepare solutions of 3,3,4-trimethyl-1,2-dioxetane (20), the first four-membered cyclic peroxide ever obtained. The thermal decomposition of 20 has been studied in the range 40-60°. The sole products of decomposition of 20 in solution were acetone and acetaldehyde. In carbon tetrachloride solution the activation energy for the decomposition of 20 was found to be ca. 23 kcal mole^{-1}.

In benzene solution 20 decomposes with the emission of blue light. The emission spectrum has a maximum at 430-440 mμ and is very similar to the emission spectrum of singlet n,π* acetone. The formation of a singlet excited carbonyl compound during the decomposition of 20 has been confirmed by means of energy transfer experiments. Luminescence during the decomposition of 20 confirms recent suggestions that four-membered cyclic peroxides are responsible for many instances of chemiluminescence and bioluminescence. The mechanism of luminescence

of 20 is discussed in terms of orbital symmetry theory and thermochemistry. The role of four-membered cyclic peroxides as intermediates in organic chemistry is also discussed.

A study of the reaction between 2-bromo-2,3-dimethyl-3-butyl hydroperoxide (18) and silver acetate has led to the synthesis and isolation of crystalline 3,3,4,4-tetramethyl-1,2-dioxetane (49). In benzene solution at 60° compound 49 decomposes to acetone with the emission of blue light.

Neither 20, nor 49 gave allylic hydroperoxides on treatment with base, so that 1,2-dioxetanes can be excluded as intermediates in the dye-photosensitized oxygenation reaction of olefins and in the reaction of tetrasubstituted β-halohydroperoxides with base. The mechanism of the latter reaction is not known with certainty, but a perepoxide intermediate is probably involved.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES

CHAPTER I

PREPARATION AND BASE-PROMOTED REACTIONS

OF SOME β-BROMOHYDROPEROXIDES

The objective of this investigation was to study the base-promoted reactions of β-bromohydroperoxides.

The dye-sensitized photooxidation of olefins affords a unique route to allylic hydroperoxides of definite structure (1,2). The hydroperoxy group is always introduced at one of the originally olefinic carbon atoms and a shift of the double bond always occurs, eq. [1], so that the reaction is very useful from a synthetic standpoint.

$$[1] \qquad {>}C^1 {=} \overset{\overset{\displaystyle H}{|}}{C^2} {-} \overset{|}{\underset{|}{C^3}} {-} \ + \ O_2 \ \xrightarrow[\text{dye}]{h\nu} \ {-}\ \overset{\overset{\displaystyle O - O - H}{|}}{\underset{|}{C^1}} {-} \overset{|}{\underset{|}{C^2}} {=}\ C^3{<}$$
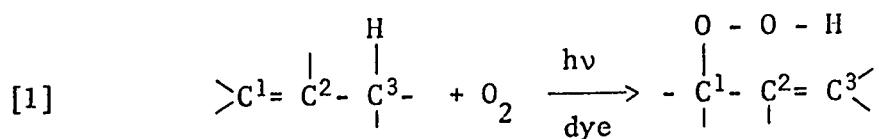
While the reaction proceeds well with tetrasubstituted olefins and somewhat less so with trisubstituted olefins, disubstituted olefins require several days irradiation for significant yields of products so that other reactions become important (3). This difficulty led to a consideration of other routes which would be as specific yet more generally useful for the conversion of olefins to allylic hydroperoxides. Thus, conversion of an olefin to the β-halohydroperoxide and then the elimination of the elements of halogen

acid would constitute a simple, two step, chemical transformation of the olefin to an allylic hydroperoxide. Such a transformation would relocate the double bond of an olefin and introduce the hydroperoxy group into the same positions as is observed in the photosensitized oxidation, eq. [2].

$$[2] \quad \underset{}{>}C^1\!\!= \overset{H}{\underset{|}{C^2}}\!\!- \overset{}{\underset{|}{C^3}}\!\!- \quad \xrightarrow[H_2O_2]{\,"X^{\oplus}"\,} \quad -\overset{\overset{\displaystyle O-H}{\underset{|}{O}}}{\underset{|}{C^1}}\!\!- \overset{H}{\underset{\underset{X}{|}}{C^2}}\!\!- \overset{H}{\underset{|}{C^3}}\!\!- \quad \xrightarrow{\text{base}} \quad -\overset{\overset{\displaystyle O-H}{\underset{|}{O}}}{\underset{|}{C^1}}\!\!- \overset{}{\underset{|}{C^2}}\!\!= C^3\!\!\underset{\searrow}{\nearrow}$$
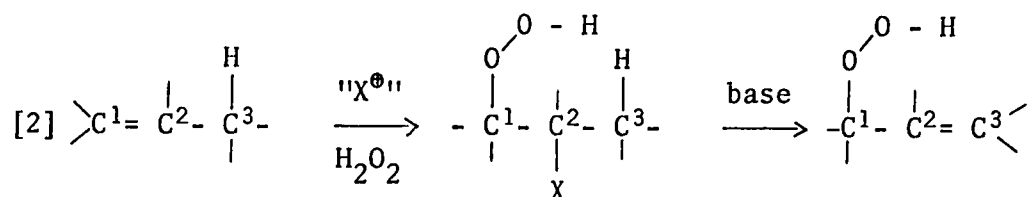
Just prior to the commencement of the present study van de Sande (4) had developed for the first time a practical synthetic route to β-halohydroperoxides. He utilized the reaction between olefins, 98% hydrogen peroxide, and N-chloroacetamide. This reaction is analogous to the widely used reaction between olefins, water and N-haloamides for the synthesis of β-halohydrins (5,6). Before that time β-halohydroperoxides had been prepared by the autooxidation of halogenated hydrocarbons (7,8), and by the reaction between olefins, hydrogen peroxide and t-butyl hypochlorite (9). These latter reactions were not very clean and gave only low yields of β-halohydroperoxides. van de Sande (4) had also discovered that the tetrasubstituted β-chlorohydroperoxide from tetramethylethylene was rapidly and cleanly converted to allylic hydroperoxide on treatment with base, eq. [2]. A decision was then taken to extend the scope of the investigation to include lesser-substituted β-halohydroperoxides. To facilitate the elimination of halogen acid in the second stage of the reaction sequence β-bromohydroperoxides were chosen in preference to

β-chlorohydroperoxides.

Cyclohexene and 2-methyl-2-butene (<u>1</u>) were chosen for the initial study since both were commercially available.

RESULTS AND DISCUSSION

An attempt was made to synthesize the desired β-bromohydroperoxides using the method of van de Sande (4). Of two available ether-soluble N-bromoamides, 1,3-dibromo-5,5-dimethylhydantoin (2) was chosen in preference to N-bromoacetamide since the latter was colored with free bromine.

Preparation of trans-2-Bromocyclohexyl Hydroperoxide (3):

The reaction between cyclohexene, one equivalent of 2 and a five-fold excess of hydrogen peroxide in ether at -40° proceeded readily. The excess hydrogen peroxide and 5,5-dimethylhydantoin could be completely removed by washing with water. The yield of trans-2-bromocyclohexyl hydroperoxide (3), 73%, was estimated by iodometric titration of the known weight of oil obtained after removal of the solvent. The purity of the crude product, 72%, was increased to 88% by low temperature recrystallization from pentane. The nuclear magnetic resonance (n.m.r.) spectrum (CCl_4) showed absorption at τ 1.04 (broad singlet) for the hydroperoxy proton, τ 5.80 (multiplet) for the methine protons, and τ 7.4-9.0 (broad) for the methylene protons of the ring. The relative peak areas were 0.89:2.0:8.1, required 1:2:8. Compound 3 took up 91% of the theoretical volume of hydrogen over platinum oxide to give trans-2-bromocyclohexanol (4), 80%, as an oil. The oil was subjected to gas-liquid chromatography (g.l.c.). The major peak had a retention time identical with that of an authentic

specimen of 4 (10). Only traces of trans-1,2-dibromocyclohexane (5)
were observed. Compound 4 was also converted to the p-bromobenzene-
sulfonyl ester which was identical with an authentic specimen (10).
When the synthesis of bromohydroperoxide 3 was attempted at 0° rapid
evolution of a gas occurred, bromine was formed and large amounts of
dibromide 5 resulted. The formation of 3 is shown in equation [3].

[3]

$$\text{Br}^{\oplus}, \text{H}_2\text{O}_2, -40°$$

3 + 5 (trace)
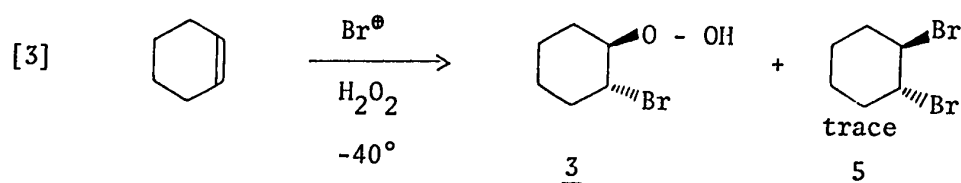
Reaction of trans-2-Bromocyclohexyl Hydroperoxide (3) with Base:

As van de Sande had reported (4) in the case of tetrasubstituted
β-bromohydroperoxides, 3 also gave a vigorous reaction with base.
However, it soon became apparent that the reaction was not proceeding
in the expected manner, eq. [4].

[4]

3 →base→X→ 6
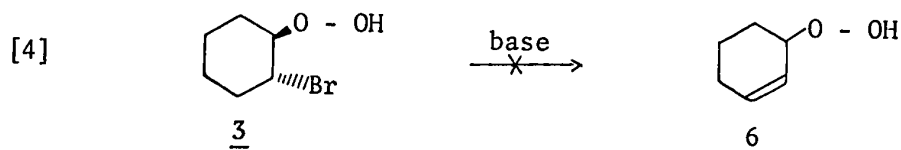
A solution of 3 in ether was allowed to react with potassium hydroxide
in ethanol at room temperature. The mixture began to boil and deposit
a white precipitate. After boiling for ca. 30 minutes the reaction
subsided. After stirring overnight at 25°, iodometric titration of an
aliquot showed that 95% of the hydroperoxide had been consumed. The
residual hydroperoxide was reduced by stirring with aqueous sodium
sulfite (11). The mixture was analyzed by g.l.c. but no trace of the

expected 3-cyclohexenol (7) could be found. The major volatile

components, cyclohexene oxide and trans-2-bromocyclohexanol (4), were

identified by comparison of the g.l.c. retention times with those of

authentic cyclohexene oxide (12), and 4 (10). Quantitative (13)

g.l.c. analysis showed that 29% cyclohexene oxide and 27% 4 had been

formed in the reaction. Cyclohexene oxide was also recovered by

distillation. The infrared spectrum of the recovered cyclohexene

oxide was identical with that of authentic cyclohexene oxide (12).

Extraction of the aqueous washings yielded trans-1,2-

cyclohexanediol (8) in ca. 2% yield. Crystals of 8 obtained by

recrystallization from benzene did not depress the melting point of

an authentic sample of 8 (14). A marked depression of melting point

was observed for a mixture of recovered 8 with an authentic sample of

cis-1,2-cyclohexanediol (15). The mass spectrum of isolated 8 showed

a parent peak at m/e 116.0835, required for $C_6H_{12}O_2$, 116.0837. The

results are summarized in equation [5].

[5]
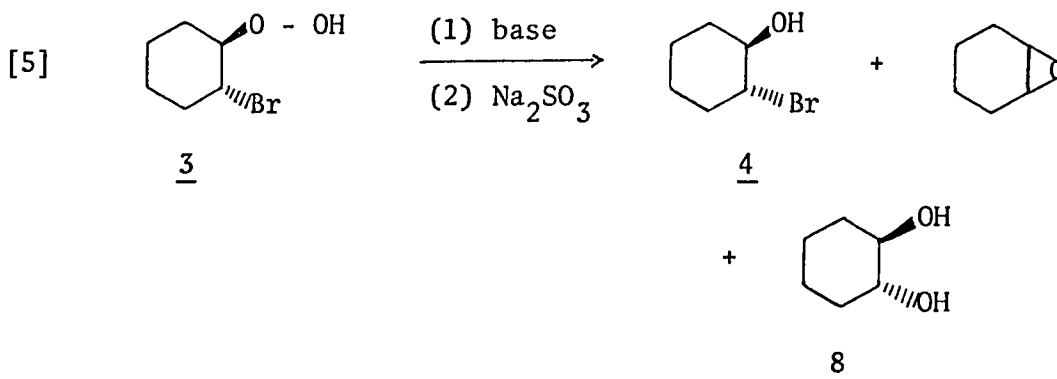
A search was made for adipaldehyde which might result from ring

cleavage, and possible products derived from it, but no such material

could be identified. Also, a search was made for 2-bromocyclohexanone,
which would be expected to be formed by base catalyzed elimination
of hydroxide ion from the secondary hydroperoxide 3 (16,17), eq. [6].

[6]
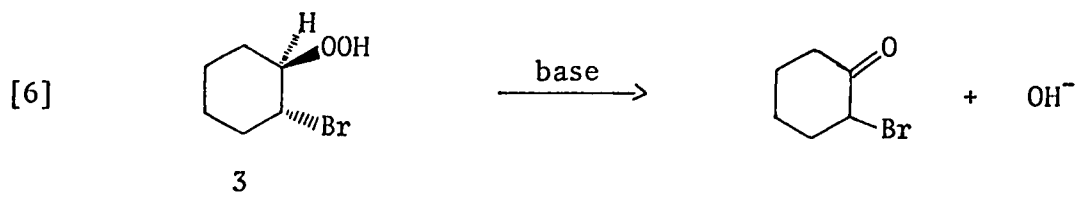
Although traces of a strongly lachrymatory substance were produced,
no further evidence of it or products derived from it could be found.

A possible reason for the poor product balance could be reaction
of cyclohexene oxide with sulfite ion during the reduction step, (18)
eq. [7].

[7]
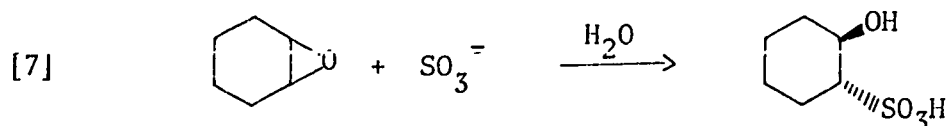
Furthermore, the white precipitate obtained in the initial reaction
of 3 with base consisted not only of potassium bromide (flame test,
and silver nitrate test), but also at least six organic components as
revealed by thin layer chromatography. These materials were not
explored any further.

Several other reactions were carried out between trans-2-
bromocyclohexyl hydroperoxide (3) and base. The reaction temperature,
time, concentration of reactants, and method of reduction (sodium
borohydride, lithium aluminum hydride) of the crude reaction mixture
were varied. In no case was any trace of cyclohexen-3-ol (7) found.

An authentic sample of 7 was prepared by the sequence shown in

equation [8].

[8]

$$9 \qquad 10 \qquad 7$$
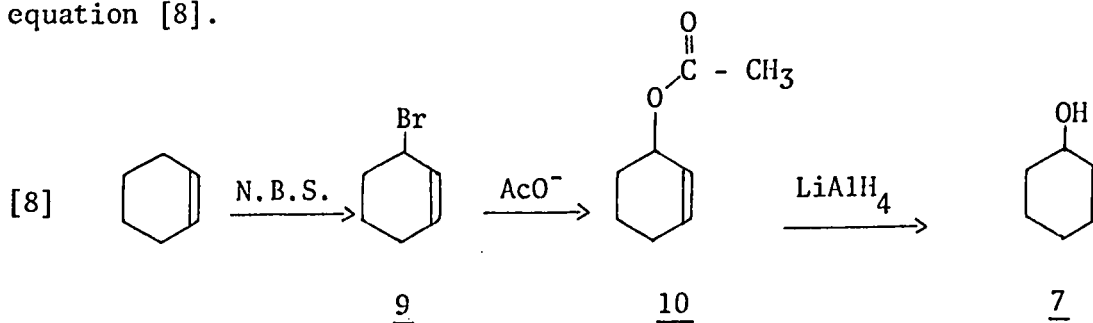
Cyclohexene was heated in refluxing carbon tetrachloride with N-bromosuccinimide (N.B.S.) and a trace of benzoyl peroxide to yield (19) 3-bromocyclohexene (9). A solution of 9 in refluxing glacial acetic acid was allowed to react (20) with sodium acetate for a few minutes to give 3-acetoxy-cyclohexene (10). Finally an ether solution of 10 was reduced with lithium aluminum hydride to give 7 as a colorless liquid. The n.m.r. spectrum (neat) of 7 showed absorption at τ 4.32 (multiplet) for the olefinic protons, τ 4.97 (singlet) for the hydroxyl proton, τ 5.89 (broad) for the methine proton and τ 7.8-8.8 (broad) for the ring methylene protons with relative peak areas 2.0:0.96:0.96:6.3, required 2:1:1:6.

Preparation of 2-Bromo-2-methyl-2-butyl hydroperoxide (11):

In the manner used for the preparation of 3, 2-methyl-2-butene (1) was converted to bromohydroperoxide 11, eq. [9]. The direction of addition is assumed to be in the Markownikov sense (see reaction using styrene). The oil obtained was found to be 92% pure by iodometric titration. From the purity and weight of the crude oil the yield of 11 was estimated to be 81%. No attempt was made to improve the purity of 11.

$$[9] \qquad \underset{\text{1}}{\begin{array}{c} CH_3 \\ {}^{\backslash}C = C{}^{/CH_3} \\ CH_3{}^{/} \qquad {}^{\backslash}H \end{array}} \qquad \xrightarrow[\substack{H_2O_2 \\ -40°}]{Br^{\ominus}} \qquad \underset{\text{11}}{\begin{array}{c} \qquad\qquad OH \\ \qquad\quad O{}^{/} \quad CH_3 \\ \qquad\quad | \qquad\; | \\ CH - C {-\!\!-} C - H \\ \qquad\quad | \qquad\; | \\ \qquad\quad CH_3 \quad Br \end{array}}$$
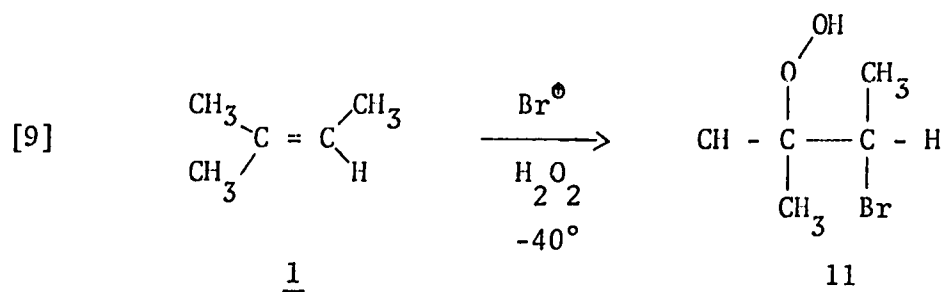
The n.m.r. spectrum (CCl_4) of 11 showed absorption at τ 1.40 (broad) for the hydroperoxy proton, τ 5.56 (quartet, J = 7 c.p.s.) for the methine proton, τ 8.32 (doublet, J = 7 c.p.s.) for the terminal methyl group protons, and τ 8.63 and 8.72 for the protons of the non-equivalent gem-dimethyl groups. The relative peak areas were 0.77:1.0:3.3:5.9, required 1:1:3:6. A carbon tetrachloride solution of bromohydroperoxide 11 was stable to heat at 60° for 21 hours. Both 3 and 11 developed a brown coloration when exposed to light for long periods but could be stored indefinitely at -10° in the dark.

At the time when the work on the preparation of β-halohydro-peroxides was well advanced, two reports appeared in the literature on this subject. Rieche, Schulz and Kirschke (21,22) synthesized β-halohydroperoxides by reaction between an olefin, hydrogen peroxide and molecular halogen. The main disadvantage of this procedure is the side reaction leading to dihalides.

Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) with Base:

van de Sande (4) had investigated the base-promoted reaction of 3-chloro-2-methyl-2-butyl hydroperoxide without being able to detect any of the desired allylic hydroperoxide (12). Preliminary experiments using 11 confirmed that the allylic hydroperoxide 12 was again not

formed but that acetone and acetaldehyde were among the major reaction

products, eq. [10].

[10]

$$CH_3 - \underset{\underset{CH_3}{|}}{\overset{\overset{O^{\diagup OH}}{|}}{C}} - \underset{\underset{Br(Cl)}{|}}{\overset{\overset{CH_3}{|}}{C}} - H \quad \xrightarrow{\text{base}}\!\!\!\!\!\times\!\!\longrightarrow \quad CH_3 - \underset{\underset{CH_3}{|}}{\overset{\overset{O^{\diagup OH}}{|}}{C}} - C\!\!\diagup^{\displaystyle CH_2}_{\displaystyle H} \quad + \quad Br^{\ominus}(Cl^{\ominus})$$

<u>11</u>   <u>12</u>
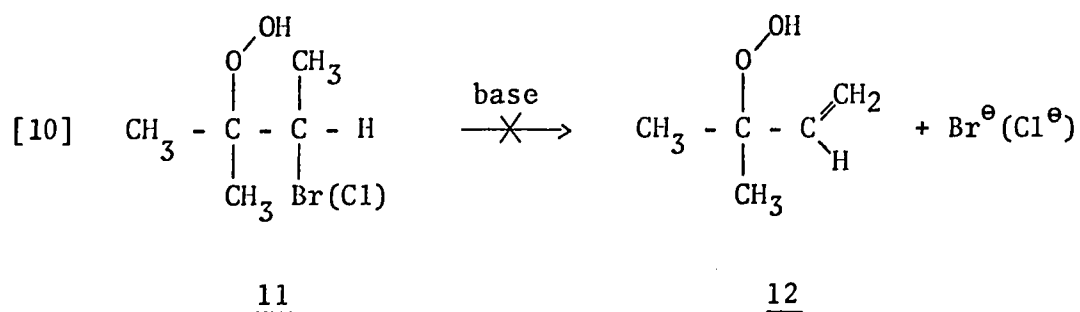
A solution of bromohydroperoxide <u>11</u> in methanol was allowed to

react with sodium hydroxide at 0°. At intervals samples were

withdrawn and quantitatively analyzed by g.l.c. The results showed

that after 10 minutes reaction, 88% acetone and 85% acetaldehyde had

apparently been formed. The apparent yields of these substances

decreased with time until after 18 hours there were present 35%

acetone, 17% acetaldehyde, and <u>ca</u>. 10% of 2,3-epoxy-2-methylbutane

(<u>13</u>). Acetone and acetaldehyde were identified by comparison of

their retention times on two different g.l.c. columns with those of

authentic samples. Thin layer chromatography of the mixture of

2,4-dinitrophenylhydrazines obtained from a portion of the reaction

mixture gave two partially resolved spots. The R_f values were equal

to those of the 2,4-dinitrophenylhydrazones of acetone and

acetaldehyde.

After 18 hours reaction with base the mixture was poured into

water and extracted with ether. G.l.c. analysis of the organic layer

showed that 10% of epoxide <u>13</u> had been formed in the reaction. This

material was isolated by distillation and by trapping it from the

effluent of the g.l.c. column. Its n.m.r. and infrared spectra were identical with those of an authentic (23) sample of 13. The undistilled residue was also examined by g.l.c. analysis. Its retention time and peak characteristics corresponded closely with those of 2-methyl-2,3-butanediol (14). It appeared to be the major reaction product. In addition, a small peak of retention time identical with that of 2-methyl-3-bromo-2-butanol (15), ca. 4%, was observed. The results are summarized in equation [11].

$$
\begin{array}{c}
\underset{\substack{O \quad CH_3 \\ | \quad | \\ CH_3 - C - C - H \\ | \quad | \\ CH_3 \; Br}}{\overset{\nearrow OH}{}} \quad \xrightarrow[\substack{18 \text{ hours} \\ 0°}]{\text{Base}} \quad
\underset{\substack{HO \quad CH_3 \\ | \quad | \\ CH_3 - C - C - H \\ | \quad | \\ CH_3 \; Br}}{} \quad + \quad
\underset{\substack{CH_3 - C - C - H \\ | \quad | \\ CH_3 \; CH_3}}{\overset{O \atop / \backslash}{}}
\end{array}
$$

[11]

11   15   13

$$
+ \quad \underset{\substack{HO \quad OH \\ | \quad | \\ CH_3 - C - C - H \\ | \quad | \\ CH_3 \; CH_3}}{} \quad + \quad \underset{CH_3}{\overset{CH_3}{}} C = O \quad + \quad \underset{H}{\overset{CH_3}{}} C = O
$$

14
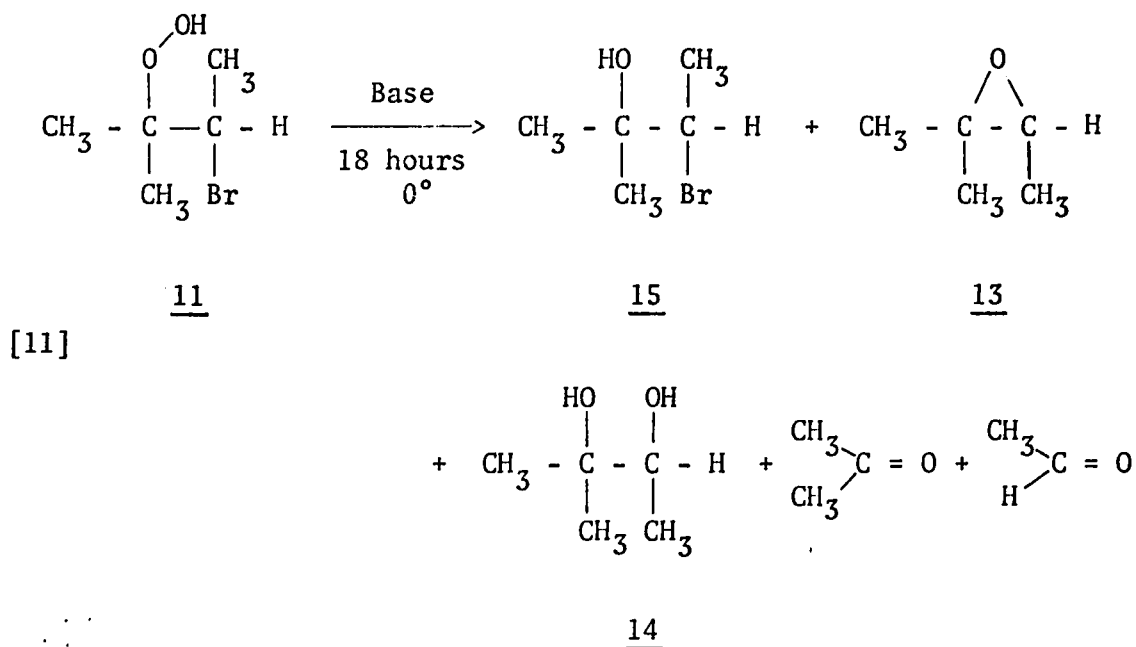
In view of the peculiar behavior of bromohydroperoxides 3 and 11 towards base, it was decided to include another olefin in the initial investigation. Styrene was chosen for its commercial availability and also because it lacks allylic protons and could not, therefore, undergo conversion to an allylic hydroperoxide.

Preparation of 2-Bromo-1-phenylethyl Hydroperoxide (16):

In the manner outlined for the preparation of bromohydroperoxides 3 and 11, styrene was converted to 16, eq. [12].

[12]

$$C_6H_5 \diagdown C = C \diagup H \quad \xrightarrow[-40°]{\substack{Br^\oplus \\ H_2O_2}} \quad C_6H_5- \underset{\underset{H}{|}}{\overset{\overset{O^{OH}}{|}}{C}} - CH_2Br$$

16
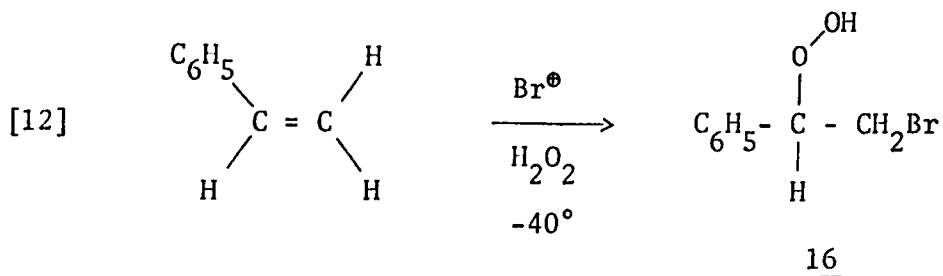
The oil obtained was 86% pure by iodometric titration. From the weight of oil and its purity the overall yield of 16 was estimated to be 78%. The n.m.r. spectrum (CCl_4) of 16 showed absorption at τ 1.00 (broad) for the hydroperoxy proton, τ 2.80 (singlet) for the phenyl protons, τ 5.07 (triplet, J = 6.5 c.p.s.) for the methine proton, and τ 6.48 (doublet, J = 6.5 c.p.s.) and τ 6.53 (doublet, J = 6.5 c.p.s.) for the non-equivalent methylene protons. The relative peak areas were 0.57:5.0:0.85:1.8, required 1:5:1:2. This material was reduced with neutral sodium sulfite (11), to 2-bromo-1-phenylethanol (17) in 87% yield. The oil obtained had similar physical properties and identical n.m.r. and infrared spectra, with those of an authentic sample (24,25). This experiment showed that the formation of β-bromohydroperoxides proceeds in the Markownikoff sense, as assumed earlier in the reaction of 2-methyl-2-butene (1).

Reaction of 2-Bromo-1-phenylethyl Hydroperoxide (16) with Base:

When a methanol solution of 16 was allowed to react with sodium hydroxide at 0°, a white precipitate began to deposit. After two hours

the mixture was separated into neutral and acidic fractions by dilution with water and extraction with pentane. After concentration and acidification the aqueous layer yielded 45% benzoic acid based·on the hydroperoxide content of 16.

The pentane layer was concentrated and a portion of it treated with 1,2-dianilinoethane (26). In this way benzaldehyde, 2.9%, was recovered as 1,2,3-triphenyltetrahydroimidazole, which did not depress the melting point of an authentic sample (26).

The bulk of the concentrate was chromatographed on neutral alumina to give a trace of styrene and a mixture of benzaldehyde and styrene oxide. Quantative g.l.c. analysis (13) of the eluent showed that 4% benzaldehyde and 45% of styrene oxide had been formed in the reaction. Styrene oxide was also recovered in 33% yield by distillation of the chromatographed material. It was identified by comparing its infrared and n.m.r. spectra with those of an authentic sample of styrene oxide (25). The results are summarized in equation [13].

$$[13] \quad C_6H_5 - \underset{\underset{H}{|}}{\overset{\overset{O-OH}{|}}{C}} - CH_2Br \quad \xrightarrow[0°]{\text{base}} \quad C_6H_5COOH \quad + \quad C_6H_5 - CHO$$

$$\underline{16}$$

$$+ \quad C_6H_5- \underset{\underset{H}{|}}{C} \overset{O}{\overset{\diagup \diagdown}{-}} CH_2$$
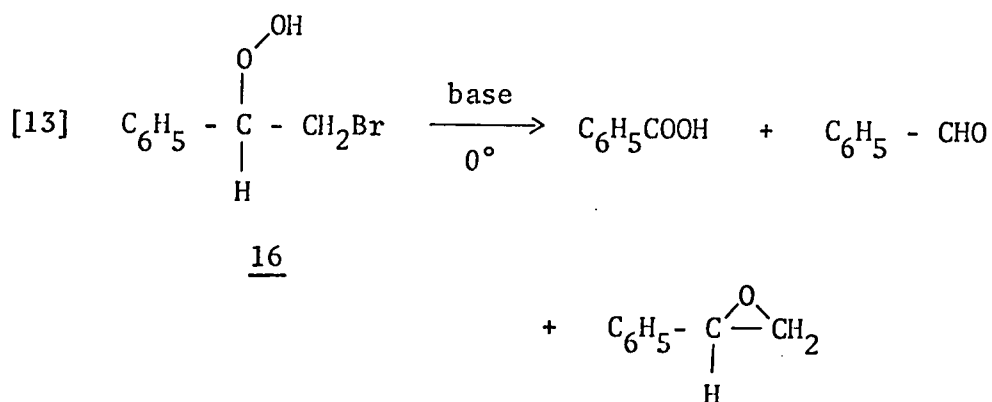
From these preliminary experiments it was obvious that the base-promoted reactions of bromohydroperoxides 3, 11, and 16 in no way

resembled the reactions of tetrasubstituted derivatives. The reaction
of 2-bromocyclohexyl hydroperoxide (3) could conceivably have been
influenced by conformational effects, but the failure of 11 to give
the allylic hydroperoxide, 12, was particularly surprising, especially
in view of its close similarity to 3-bromo-2,3-dimethyl-2-butyl
hydroperoxide (18), eq. [14], (4).

[14]

$$
\begin{array}{ccc}
& \overset{\displaystyle O^{OH}}{\underset{\displaystyle CH_3}{\underset{|}{C}}} \; \overset{\displaystyle CH_3}{\underset{\displaystyle Br}{\underset{|}{C}}} - H & \xrightarrow{\;\;base\;\;} \!\!\!\!\! X \\
CH_3 - & &
\end{array}
$$

11 → (base, X) → 12

18 → (base) → 19 (77%)
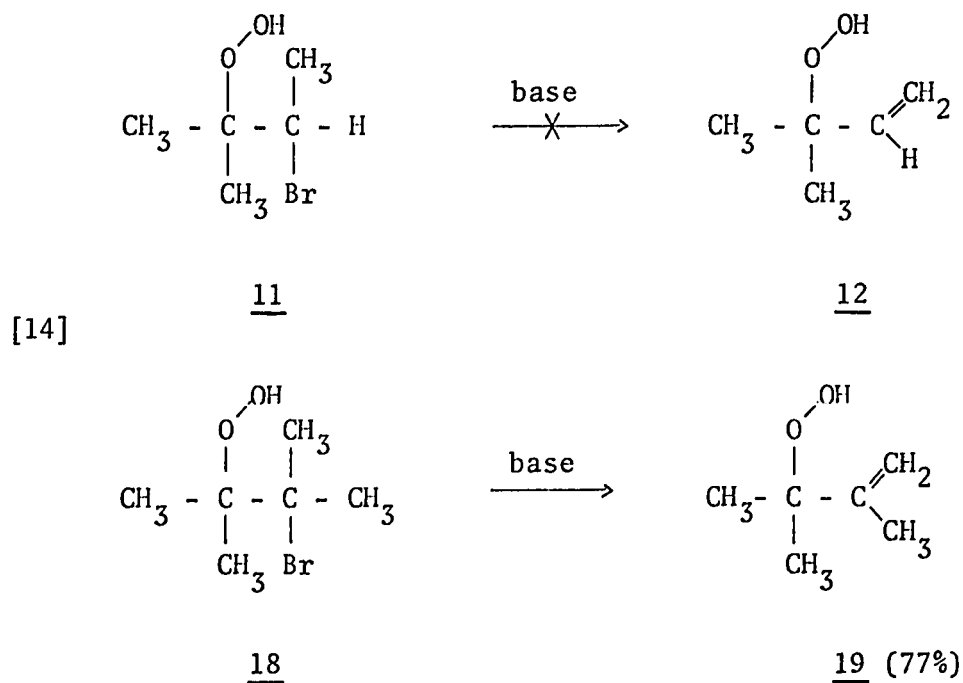
The formation of cleavage products from the base-promoted reactions
of 2-bromo-1-phenylethyl hydroperoxide and also in the early stages
of the reaction of 11 with base was in keeping with some observations
of other workers which appeared during the course of this work.

Richardson, Peters and Konopka (27) reported that acetone and
formaldehyde are rapidly produced in the reaction of 1-chloro-2-methyl-
2-propyl hydroperoxide with base, eq. [15].

[15] $CH_3 - \overset{\overset{\displaystyle O-OH}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}} - CH_2Cl$ $\xrightarrow{\text{base}}$ $\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{>}}C = O$ + $\overset{\displaystyle H}{\underset{\displaystyle H}{>}}C = O$
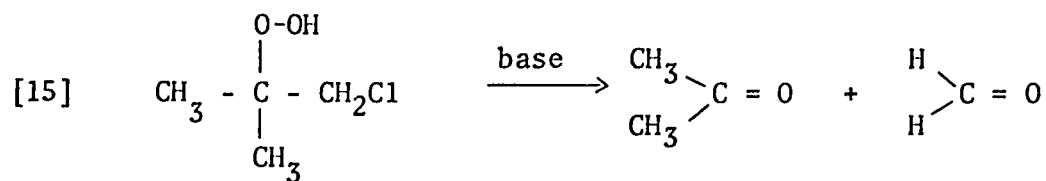
In addition to these products, Schulz, Rieche and Kirschke (21) obtained some isobutylene oxide in the reaction of the corresponding 1-bromo derivative with base. A similar cleavage was observed by Dulog and Voght (28) in the base-promoted reaction of 2-methyl-2-hydroperoxy-propionitrile, eq. [16].

[16] $CH_3 - \overset{\overset{\displaystyle O^{\nearrow OH}}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}} - C \equiv N$ $\xrightarrow{\text{base}}$ $\overset{\displaystyle CH_3}{\underset{\displaystyle CH_3}{>}}C = O$ + $O = C = N^{\ominus}$
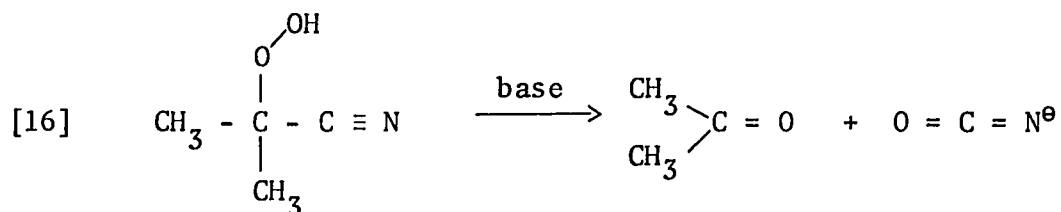
These hydroperoxides have the substituent on the terminal carbon so a simple elimination route to allylic hydroperoxides is not possible. It was suggested (21,27,28) that the cleavage products might have resulted via the thermal decomposition of intermediate four-membered cyclic peroxides. Such compounds are more properly named as derivatives of 1,2-dioxetane (29). If such a mechanism could occur in the present system, then the base-promoted reaction of 3-bromo-2-methyl-2-butyl hydroperoxide (11) would become understandable, eq. [17].

[17]

$$CH_3 - \overset{\overset{\displaystyle O^{\nearrow OH}}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}} - \overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle Br}{|}}{C}} - H \quad \xrightarrow[0°]{\text{base}} \quad CH_3 - \overset{\overset{\displaystyle O-O}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}} - \overset{|}{\underset{\underset{\displaystyle CH_3}{|}}{C}} - H \quad + \quad Br^{\ominus}$$

<u>11</u>   <u>20</u>

Δ g.l.c.
analysis   0°

$$\underset{CH_3 \quad CH_3}{\overset{\overset{\displaystyle O}{\|}}{C}} \quad + \quad \underset{CH_3 \quad H}{\overset{\overset{\displaystyle O}{\|}}{C}} \qquad\qquad \text{Products}$$
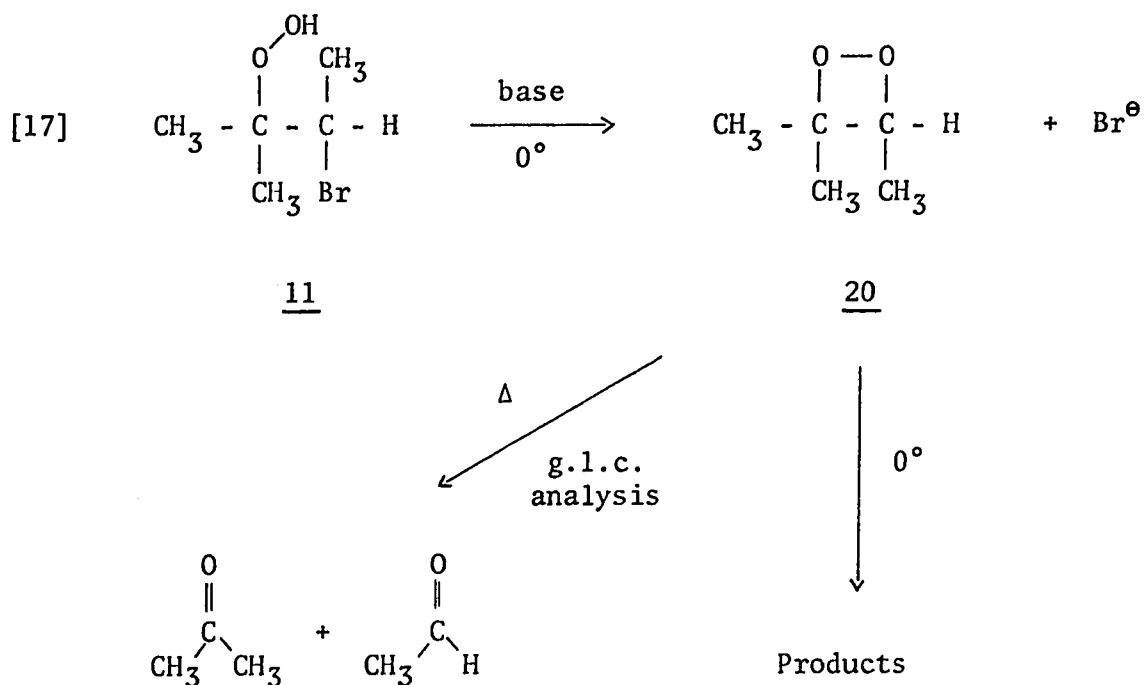
If the intermediate 20 underwent a further slow reaction to give the
ultimate products, was stable at 0° but decomposed on g.l.c. analysis,
then the gradual decline in the apparent yield of acetone and
acetaldehyde would reflect the slow reaction of 20 to give other
products. If 3,3,4-trimethyl-1,2-dioxetane (20) was stable at 0°
there existed the possibility of isolating this and other members of
this unknown class of compounds.

EXPERIMENTAL

Melting points and boiling points reported are not corrected. Refractive indices were measured on a Bausch and Lomb Abbe-3 L Refractometer. Infrared spectra were recorded on Perkin-Elmer Model 421 and Model 337 spectrophotometers and only characteristic absorption bands are cited. N.m.r. spectra were determined with Varian analytical spectrometers, Models A-60 and A56/60 with tetramethylsilane (TMS) as internal standard. G.l.c. analysis was carried out on Aerograph 202 and A-90-P3 gas chromatographs. Mass spectra were obtained on A.E.I. MS-9 and MS-12 mass spectrometers.

All preparations and reactions of β-bromohydroperoxides were carried out behind shields. Apparatus containing these materials was manipulated with the aid of clamps where possible. The hands were protected with heavy canvas gloves and a face shield was worn. It was important to use scratch-free glassware and uncontaminated, teflon-coated stirrers. At no time during this work did an explosion occur, but rapid decomposition of some bromohydroperoxides did occur if allowed to come into contact with metallic particles or surfaces.

Hydroperoxides were estimated iodometrically using the procedure of Organic Synthesis (30). Solutions and solvents were dried over anhydrous magnesium sulfate unless indicated otherwise.

trans-2-Bromocyclohexyl Hydroperoxide (3):

To 50 ml of anhydrous ether stirred at -40°, 98% hydrogen peroxide (17.0 g, 0.5 mole) was added in small portions. Each addition caused a very rapid increase in temperature. The additions were made at such a rate that the temperature did not rise above -30°. Sometimes solid hydrogen peroxide was formed but this could be dissolved by continued stirring. On reattaining -40°, cyclohexene (8.2 g, 0.1 mole) was added in one portion. Then 1,3-dibromo-5,5-dimethylhydantoin (2) (14.3 g, 0.05 mole) was slowly added in powder form. If large amounts of 2 were added the solution became colored with bromine. This problem was overcome by adding solid 2 as a fine stream from a small-bore funnel. When the addition of 2 was complete the cooling bath and its contents were allowed to warm slowly to ca. 10°. When the mixture had become homogeneous 50 ml water was added and the mixture was allowed to stir for a few minutes. The organic layer was then separated and extracted three times with 50 ml water. To check the efficiency of extraction each aqueous extract was stirred with platinum oxide. While the first extract evolved a large amount of oxygen the fourth extract gave virtually no gas evolution. After destroying the excess hydrogen peroxide each extract was evaporated to dryness. The weights of 5,5-dimethylhydantoin m.p. 172°, reported (31) 172-175°, were 5.35 g, 0.9 g, 0.25 g, and 0.15 g (104%).

The organic layer was dried and concentrated at room temperature. The crude product, 19.8 g of an oil, contained 72% of the theoretical hydroperoxide content as determined by iodometric titration. The overall yield was 73%. The crude material was recrystallized from

100 ml pentane at -78°. The crystals melted at ca. -20° to a colorless liquid. Removal of residual pentane under reduced pressure gave oil with 88% of the theoretical peroxide titer. The n.m.r. spectrum is described in the results and discussion section.

trans-2-Bromocyclohexanol (4) from trans-2-Bromocyclohexyl Hydroperoxide (3):

Hydrogenation of 1.95 g (88% pure, 8.8 mmole) of 3 in 25 ml ether over platinum oxide at 0° and atmospheric pressure resulted in the rapid uptake of 178 ml (S.T.P.), 91% (based on the hydroperoxide content of 3) of hydrogen. The dried, filtered ether solution was concentrated to give an oil. G.l.c. analysis of the oil on a 5 ft. x 1/4 in. column of 10% QF-1 on Chromosorb W at 150° showed the presence of a trace of trans-1,2-dibromocyclohexane (5). The major product had a g.l.c. retention time identical with that of an authentic sample (10) of trans-2-bromocyclohexanol (4). A portion of the oil was converted to the p-bromobenzenesulfonyl ester of 4 (10), with melting point and mixture melting point with authentic material (10) 90.0-90.5°; reported (10) m.p. 91.9-92.3°.

Reaction between trans-2-Bromocyclohexyl Hydroperoxide (3) with base:

A solution of potassium hydroxide (5.6 g, 0.1 mole) in 25 ml ethanol was added at 25° to a solution of 3 (19.5 g, 80% pure, 0.08 mole) in 100 ml ether. Within 2-3 minutes boiling commenced and continued for ca. 30 minutes. The mixture was allowed to stir overnight at 25° by which time a white precipitate had formed. Iodometric titration of an aliquot of the slurry showed that 95% of

the hydroperoxide had been consumed. The mixture was filtered and the filtrate stirred vigorously with 50 ml of aqueous 2 M sodium sulfite (11) for 1 hour. The organic layer was then separated, washed twice with water, dried and the solvent removed through a vigreaux column.

The residual oil had a pungent odor. The infrared spectrum (neat) showed broad strong absorption in the region 3600-3200 cm^{-1} and a medium intensity absorption with several maxima between 1735 and 1715 cm^{-1}. The major volatile components were found by g.l.c. analysis to be cyclohexene oxide and trans-2-bromocyclohexanol (6). These compounds were identified by comparison of their retention times with those of authentic samples on a QF-1 column and on a 5 ft. x 1/4 in. column of 20% DEGS on Chromosorb W at 150°. The mixture was analyzed by quantitative g.l.c. (13) using benzaldehyde as internal standard. The molar response factors were benzaldehyde 100, cyclohexene oxide 46.1, trans-1,2-dibromocyclohexane 147, and trans-2-bromocyclohexanol 101. The yields were cyclohexene oxide 29%, trans-1,2-dibromocyclo-hexane 2%, and trans-2-bromocyclohexanol 27%.

Attempted distillation of a portion of the oil resulted in decomposition soon after boiling began (pot temperature 100°, 10 mm). A small amount of colorless liquid which had collected in the condenser was taken up in carbon tetrachloride. The infrared spectrum of this material was identical with that of authentic cyclohexene oxide (12).

The aqueous extract remaining from the original reaction was extracted several times with ether and the dried extracts concentrated.

The viscous oil (0.3 g) which remained, crystallized on standing.
The material was recrystallized from benzene and then melted at
96.0-97.5°. The mass spectrum of this substance showed a parent peak
at m/e 116.0835. $C_6H_{12}O_2$ requires 116.0837. It was identified as
trans-1,2-cyclohexanediol (8) by its mixture melting point with an
authentic sample (14) of 8, m.p. 96-101°. The mixture melting point
with authentic cis-1,2-cyclohexanediol (15) was 65-74°. The reported
(32) melting point for the cis-diol is 96-98°.

The precipitate obtained on filtering the initial reaction
mixture was taken up in a small amount of water. The solution was
made acidic with 6N hydrochloric acid and extracted with chloroform.
The organic layer was dried and the solvent removed to yield 0.8 g of
a viscous oil. A thin layer chromatogram of this material on silica
gel G.F. 254 as adsorbent and ether as eluent indicated that at least
six components were present. The material was not investigated
further.

Several other reactions between 3 and base gave similar results.
The reaction temperature and time, concentration of reactants, and
method of reduction (sodium borohydride, lithium aluminum hydride)
of the crude reaction mixture were varied. In no case was any of
cyclohexen-3-ol (7) found.

trans-2-Bromocyclohexanol (4):

The method of Winstein and co-workers (10) was used to prepare
4 from cyclohexene (12.8 g, 0.156 mole). The product was fractionated
to yield 4 (17 g, 61%), b.p. 64.5-65.5° (2.7 mm) and b.p. 78.5° (7 mm);
reported (10) b.p. 72° (3 mm). The compound was converted (10) to

the p-bromobenzenesulfonyl ester, m.p. 90.0-90.5°; reported (10), m.p. 91.9-92.3°.

Cyclohexene oxide:

The method of Organic Synthesis (12) was used to prepare cyclohexene oxide from 2-bromocyclohexanol (5.72 g, 0.032 mole) and sodium hydroxide. The product was fractionated to yield cyclohexene oxide (2.5 g, 80%), b.p. 129-134°; reported (12) b.p. 129-134°. This fraction was analyzed by g.l.c. and found to be 99% pure.

trans-1,2-Cyclohexanediol (8):

The method of Winstein (14) was used to prepare 8 by acid-catalyzed hydration of cyclohexene oxide (1.89 g, 19.3 mmole). The yield of 8 after recrystallization from benzene was 0.922 g (40%), m.p. 96-98°; reported (14), m.p. 103-104°. The mixture melting point with authentic cis-1,2-cyclohexanediol (15) was 65-74°.

trans-1,2-Dibromocyclohexane (5):

The method of Organic Synthesis (34) was used to prepare 5 from cyclohexene (12.3 g, 0.15 mole) and bromine (21 g, 0.13 mole). The distilled product (28.7 g, 77% yield), b.p. 98-99° (13 mm), was impure as revealed by n.m.r. analysis. Crude 5 was passed through a short column of alumina (Grade 1) as a solution in pentane. The pentane was removed under reduced pressure at 25° and the residue refractionated. The boiling point of the purified 5 was unchanged. Reported (33) b.p. 99-103° (16 mm). Neither the n.m.r. spectrum, nor the g.l.c. chromatogram of purified 5 showed any evidence of impurity.

3-Bromocyclohexene (9):

Cyclohexene (9.9 g, 0.12 mole), N-bromosuccinimide (17.8 g, 0.10 mole) and a trace of benzoyl peroxide were heated in 100 ml of refluxing carbon tetrachloride for a period of 72 hours (19). The mixture obtained was filtered to remove succinimide and the filtrate fractionated to yield 9, (8.0 g, 50% based on N-bromosuccinimide used), b.p. 30° (1.3 mm); reported (19) b.p. 55-57° (11 mm). The product decolorized alkaline permanganate, and also bromine water, and gave a positive Belstein test. G.l.c. analysis indicated a maximum of 4% impurity.

Cyclohexen-3-ol (7):

A solution of 9 (8.0 g, 0.05 mole) and anhydrous sodium acetate (4.1 g, 0.05 mole) in 50 ml glacial acetic acid was heated at reflux for 5 minutes (20). A precipitate of sodium bromide formed rapidly (silver nitrate test). The cooled mixture was filtered and the precipitate washed with glacial acetic acid. The filtrate and washings were neutralized to pH 8 using aqueous 10% sodium carbonate and the resulting mixture extracted with ether. The dried ether extract, containing 3-acetoxy-cyclohexene (10), was slowly added to a stirred slurry of lithium aluminum hydride in ether at 25°. After stirring overnight the mixture was treated with 15% aqueous potassium hydroxide to destroy the excess hydride. The dried ether layer was fractionated to yield cyclohexen-3-ol (2.0 g, 41%), b.p. 53° (6 mm); reported (34), b.p. 63-65° (12 mm). The n.m.r. spectrum is described in the results and discussion section.

3-Bromo-2-methyl-2-butyl Hydroperoxide (11):

The procedure described for the preparation of 3 was used to prepare a crude sample of 11 from 7.0 g (0.1 mole) of 2-methyl-2-butene (1), 14.3 g (0.05 mole) of the hydantoin, 2, and 17.0 g (0.5 mole) of 98% hydrogen peroxide in 50 ml anhydrous ether. The oil obtained was freed of residual ether by storing it at 0.1 mm pressure for 2 hours. The residual oil, 16 g, had 92% of the theoretical hydroperoxide content by iodometric titration. The overall yield of 11 was 80%. The n.m.r. spectrum has been described in the results and discussion section.

A carbon tetrachloride solution of 11 showed no change in the n.m.r. spectrum and negligible loss of hydroperoxide content (iodimetry) after being heated at 60° for 21 hours. However, 11 did develop a brown coloration when exposed to light for long periods but could be stored indefinitely at -10° in the dark.

Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) with base:

Preliminary experiments showed that 11 was not converted by base to the allylic hydroperoxide, 12. Prior to reduction of the residual peroxides with sodium borohydride the basic reaction mixture gave a positive Schiff's test for aldehyde. Acetone and acetaldehyde were detected among the products by g.l.c. analysis. The experiment was repeated and the yield of acetone and acetaldehyde monitored continuously.

A solution of 11 (0.6242 g, 90.5% pure, 3.09 x 10^{-3} mole) in 5 ml methanol was placed in a serum-capped flask immersed in an ice-water bath. Base (0.166 g sodium hydroxide, 0.4 ml water and 0.6 ml methanol)

was added by means of a syringe. The total weight of an identical
mixture was found to be 5.415 g. Weighed aliquots of the mixture
(1.0 ml), were removed at intervals and placed in a serum-capped flask
together with a known weight of 2,3-dihydropyran as internal standard.
Each sample was analyzed quantitatively (13) on a 5 ft. x 1/4 in.
column of 10% Carbowax 1500 on Chromosorb W at 50°. The products were
identified by comparison of their g.l.c. retention times with those of
authentic samples. The estimated yields of acetone and acetaldehyde
decreased with time as shown in the table:

TIME (minutes)	ACETONE %	ACETALDEHYDE %
18	88.3	85.4
52	81.2	85.1
82	76.4	77.1
112	73.5	75.7
1120	34.6	16.8

The quoted yields are based on the hydroperoxide content of the
starting material. The molar response factors were determined to be
2,3-dihydropyran 100, acetone 91.6, acetaldehyde 67.0. Thin layer
chromatography on silica gel GF-254 using benzene as eluent, of a
mixture of 2,4-dinitrophenylhydrazones obtained from an aliquot of
the ultimate reaction mixture gave two partially resolved spots. The
The R_f values were equal to those of the 2,4-dinitrophenylhydrazones
of acetone and acetaldehyde.

The ultimate reaction mixture was poured into 200 ml water and
the mixture was extracted with ether. An aliquot of the dried organic

layer analyzed by g.l.c. on the Carbowax column at 50°, showed that
ca. 10% of 2,3-epoxy-2-methylbutane (13) had been formed in the
reaction.

The remainder of the organic layer was carefully concentrated
through a 4 ft. Podbielniak column. From the residual oil 13 was
isolated by trapping it from the effluent of the g.l.c. column. Its
n.m.r. and infrared spectra were identical with those of authentic 13
(23). The major component of the residual oil was eluted from the
g.l.c. column much later than 13. Its retention time and peak
characteristics corresponded closely with those of 2-methyl-2,3-
butanediol (14). In addition a small peak of retention time identical
with that of 3-bromo-2-methyl-2-butanol (15) (ca. 4%), was observed.

2,3-Epoxy-2-methylbutane (13):

Solid 1,3-dibromo-5,5-dimethylhydantoin (2) (143 g, 0.05 mole)
was added in small portions to a stirred mixture of 2-methyl-2-butene
(1) (7.0 g, 0.1 mole) and 70 ml water, at such a rate that the
temperature did not exceed 30°. Stirring was continued until all the
reactants had dissolved and a dense oil had separated. The oil was
taken up in 50 ml ether and washed four times with 25 ml water. The
ether solution was dried and evaporated to constant weight to give
3-bromo-2-methyl-2-butanol (15) (12.7 g, 76%). The crude material
decomposed on attempted distillation so it was used in an impure state.
A mixture of 15 (12.0 g, 71.8 mmole) and 20 ml water was cooled with
stirring to 0°. Sodium hydroxide (4.0 g, 0.1 mole) in 10 ml water was
added over a period of 30 minutes. When 15 had completely dissolved
the solution was extracted once with 20 ml of methylene chloride then

twice with 10 ml methylene chloride. The dried extracts were
fractionated on a Nestor-Faust annular teflon spinning band column.
The fraction b.p. 68-69° (699 mm) was collected (1.5 g, 27%),
n_D^{24} = 1.3846; reported (23) b.p. 74-78°, n_D^{18} = 1.3896. The n.m.r.
spectrum (CCl_4) showed absorption at τ 7.32 (quartet, J = 5.5 c.p.s.)
for the methine proton, τ 8.78 (doublet, J = 5.5 c.p.s.) for the
terminal methyl group, and τ 8.78 and 8.82 for the protons of the
non-equivalent gem-dimethyl groups. The relative peak areas were
1.02:8.99, required 1:9. The infrared spectrum showed absorptions at
1252, 863 and 752 cm^{-1} characteristic (35) of epoxides.

2-Methyl-2,3-butanediol (14):

A mixture of 13 (3.7 g, 43 mmole), 12 ml water and two drops of
concentrated sulfuric acid were shaken with cooling under the tap
until the sharp odor of 13 had faded. The homogeneous solution was
then neutralized with 10% aqueous sodium carbonate. The water was
removed by distillation under reduced pressure and the residue washed
repeatedly with a total of 100 ml ether. The ether solution was dried
and concentrated. The residual oil was distilled to give 14 (2.35 g,
53%) b.p. 63-64° (4.2 mm), n_D^{28} = 1.4361; reported (36) b.p. 74° (105 mm)
n_D^{25} = 1.4363. The infrared spectrum (neat) showed absorptions at
3380, 1170 and 1100 cm^{-1}. The n.m.r. spectrum (CCl_4) showed
absorptions at τ 6.03 (broad singlet) due to the hydroxyl protons,
τ 6.51 (quartet, J = 6.5 c.p.s.) for the methine proton, τ 8.92
(doublet, J = 6.5 c.p.s.) for the terminal methyl group, and τ 8.88
and 8.91 (singlets) for the protons of the non-equivalent gem-dimethyl
groups. The relative areas were 2.30:1.13:8.60, required 2:1:9.

2-Bromo-1-phenylethyl Hydroperoxide (16):

The procedure described for the preparation of the bromohydro-peroxide, 3, was used to prepare a crude sample of 16 from redistilled styrene (10.4 g, 0.1 mole), the hydantoin, 2, (14.3 g, 0.05 mole) and 98% hydrogen peroxide (17 g, 0.5 mole), in 50 ml ether. The oil obtained was freed of residual ether by storing it at 0.5 mm pressure for 2 hours. The remaining oil, 19.8 g, had 86% of the theoretical hydroperoxide content by iodometric titration. The overall yield of 16 was, therefore, 78%. The n.m.r. spectrum has been described in the results and discussion section.

2-Bromo-1-phenylethanol (17) from 16:

A solution of 16 (13 g, 86% pure, 51.5 mmole) in 100 ml ether was stirred vigorously overnight with 13 g (two equivalents) of sodium sulfite (11) dissolved in the minimum of water. At this time the organic layer was separated, dried and concentrated under reduced pressure at 25°. Distillation of the residual oil yielded 9.2 g, 87% (based on the hydroperoxide content of 16), of 2-bromo-1-phenylethanol (17) b.p. 78-79° (0.3 mm), n_D^{26} = 1.5763; reported (25) b.p. 120-123° (5 mm), n_D^{19} = 1.5785. The n.m.r. and infrared spectra were identical with those of an authentic specimen (24,25) of 17.

Reaction between 2-Bromo-1-phenylethyl Hydroperoxide (16) and Base:

A solution of sodium hydroxide (4.0 g, 0.1 mole) in 15 ml methanol was added to a stirred solution of 16 (20.6 g, 78% pure, 0.074 mole) in 100 ml of methanol at 0°. A white precipitate soon began to form. After 2 hours at 0°, 200 ml water was added and the resulting mixture

was extracted four times with 100 ml pentane. The aqueous layer was
concentrated to a small volume and made acidic with 6N hydrochloric
acid. An oil separated which began to crystallize. The mixture was
extracted with 100 ml ether and the ether was dried. Evaporation of
the ether left an oil which crystallized on standing, 4.3 g. The
solid, recrystallized from methanol, had m.p. and mixture melting point
with benzoic acid 119-120°. The yield was 45% based on the
hydroperoxide content of 16.

The pentane solution was concentrated to a small volume through
a 4 ft. Podbielniak column. The odor of benzaldehyde was detected
in the concentrate. Benzaldehyde was isolated as a derivative by
adding 2 g of 1,2-dianilinoethane (26) in 20 ml methanol to 21% of
the concentrate. The solution was left at 0° overnight. The crystals
which separated were filtered to give 0.133 g, 2.9% (based on the
hydroperoxide content of 16), of 1,2,3-triphenyltetrahydroimidazole,
m.p. and mixture melting point with authentic (26) material 131-131.5°;
reported (26) m.p. 137°.

The remainder of the concentrate was adsorbed on a 1.5 x 30 cm
column of neutral alumina and eluted with 100 ml pentane then 200 ml
ether. The eluents were analyzed by g.l.c. on a 9.5 ft. x 1/4 in.
column of 10% Ucon-50-HB-5100 on Chromosorb W at 158°. The pentane
eluent contained only styrene, and the ether eluent only benzaldehyde
and styrene oxide. Further elution of the column with 200 ml ether
gave no further product. Quantitative (13) g.l.c. analysis of the
ether eluent using ethyl benzoate as internal standard showed that 4%
benzaldehyde and 45% styrene oxide (based on the hydroperoxide content

of 16) had been formed in the reaction.

Concentration of 63% of the ether eluent and distillation of the residual oil yielded 1.34 g,. 15% of styrene oxide, b.p. 53° (2.8 mm), n_D^{26} = 1.5312; reported (25) b.p. 65° (5 mm), n_D^{20} = 1.5340. The n.m.r. and infrared spectra of this product were identical with those of an authentic sample (24) except for a weak adsorption at 1700 cm^{-1} in the infrared.

2-Bromo-1-phenylethanol (17):

The method of Buckles and Maurer (24) was used to prepare 17 from styrene. Redistilled styrene (10.4 g, 0.1 mole) was added with cooling to a solution of 1,3-dibromo-5,5-dimethylhydantoin (2) in 100 ml of 50:50 v/v dioxane-water containing a crystal of p-toluenesulfonic acid. The heavy oil which formed was separated, washed with water and dried. The oil was fractionated to yield 17 (8.5 g, 43%) b.p. 95-96° (1.6 mm) n_D^{28} = 1.5742; reported (25) b.p. 120-123 (5 mm). The n.m.r. spectrum (CCl$_4$) showed absorption at τ 2.82 (singlet) due to the phenyl protons, τ 5.33 (multiplet) due to the methine proton, τ 6.32 (singlet) due to the hydroxyl proton, and τ 6.59-6.79 (multiplet) due to the methylene protons. The relative peak areas were 5.0:1.0:1.02:1.93; required 5:1:1:2.

Styrene oxide:

A solution of the bromohydrin, 17 (5.0 g, 25 mmole), in 25 ml ether was stirred with 1 g sodium hydroxide dissolved in 30 ml water at 10°. After one hour the ether layer was separated, washed with 25 ml water and dried. The solvent was removed through a 4 ft.

Podbielniak column and the residue fractionated to yield 1.88 g (61%)
of styrene oxide, b.p. 61° (4.5 mm) n_D^{28} = 1.5319; reported (25)
b.p. 65° (5 mm), n_D^{20} = 1.5340.

CHAPTER II

ISOLATION AND PROPERTIES OF 3,3,4-

TRIMETHYL-1,2-DIOXETANE

In Chapter I evidence was presented to show that representative disubstituted and trisubstituted β-bromohydroperoxides did not undergo the base-promoted conversion to allylic hydroperoxides so characteristic (4) of tetrasubstituted β-halohydroperoxides. Some of the results were explicable if substituted 1,2-dioxetanes were formed in the primary step. It appeared from the initial experiments with 3-bromo-2-methyl-2-butyl hydroperoxide (11) that it might be possible to isolate the primary intermediate, 3,3,4-trimethyl-1,2-dioxetane (20), eq. [18].

[18]

CH$_3$- C - C - H $\xrightarrow[0°]{\text{base}}$ CH$_3$ - C - C - H

11

20
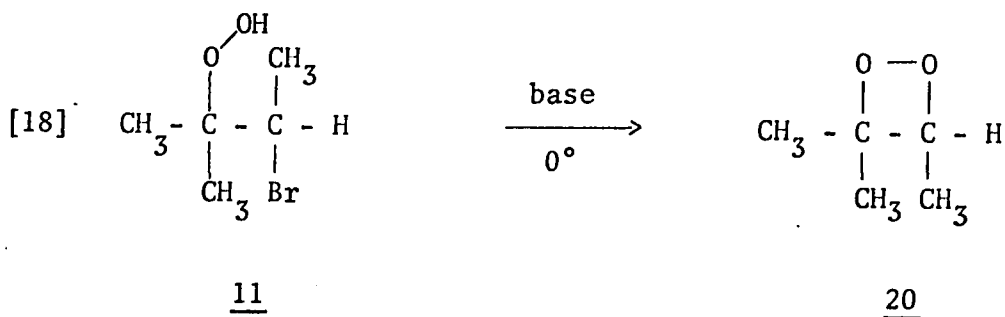
The isolation of 20 would be important for several reasons:

1). No authenticated preparation of a 1,2-dioxetane has been described in the literature.

2). A study of the properties of such a compound would permit a

critical examination of earlier reports that such compounds had been isolated, or had occurred as reaction intermediates.

3. Such compounds appear to be the source of some occurrences of chemiluminescence and bioluminescence.

In this chapter the isolation of 20 as a solution in organic solvents is described. The structure of 20 was deduced from its chemical properties, its spectra, and its facile decomposition to give acetone and acetaldehyde. The properties of 20 are discussed in relation to the three points mentioned above.

RESULTS

Rates of Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11)
with Base at 0°:

The reaction of 11 with base was studied kinetically in order to

establish the best conditions for the isolation of 20.

(a) Appearance of Bromide Ion:

Reaction mixtures were prepared by combining 50 ml of 0.052 M 11,

in anhydrous methanol, with 7.5 ml of water at 0°. Then, 2.5 ml of

aqueous 1 M, 2 M or 3 M sodium hydroxide were added. Known fractions

of the reaction mixture were removed at intervals, quenched with

aqueous acetic acid and the aqueous extracts titrated by the Volhard

method for liberated bromide ion. The rate constants for the second

order reaction between 11 and base were calculated using the formula

in equation [19] (37a).

[19]
$$\frac{1}{a-b} \ln \frac{b(a-x)}{a(b-x)} = k_2 \cdot t$$

By plotting the left hand side of equation [19] versus the time, a

straight line was obtained whose slope gave the rate constant k_2.

Difficulty arose in the kinetic treatment of the reaction mixture

where 1.0 M sodium hydroxide was used. The actual concentration of

11 was 0.0449 M while the base concentration was 0.0433 M. Although

the initial concentrations were different, equation [19] could not be

used because the logrithmic term did not change appreciably during the

reaction. Consequently, use was made of the approximate relationship of equation [20] (37b).

[20] $$\frac{1}{d-x} = k_2 t + \frac{1}{d}$$

In this equation the term "d" is the average initial concentration of the reactants. By plotting the left hand side of equation [20] versus the time, a straight line was obtained whose slope gave the rate constant k_2. The data obtained at the three base concentrations are given in Tables I, II and III. From these tables it can be seen that the average rate constant for the reaction, k_2, is 1.36×10^{-3} liter $mole^{-1} sec^{-1}$. An example of one of the plots, where 1.0 M sodium hydroxide was used, is shown in Figure 1.

In the case where 1.0 M sodium hydroxide was used, iodometric titration (30) of the total peroxide content was also performed. The rate of loss of the total peroxide content was much slower than the rate of appearance of bromide ion as shown in Figure 2. This result showed that the primary reaction product was still peroxidic, eq. [21].

[21]
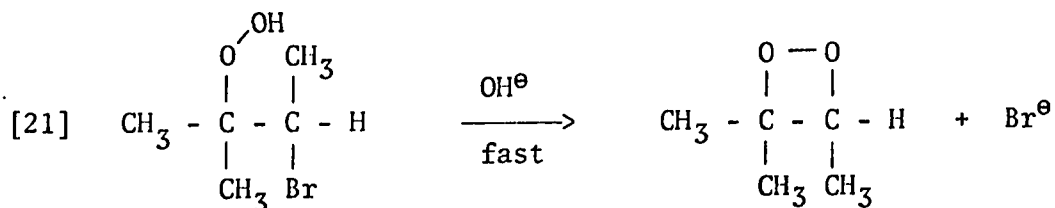
Isolation of 3,3,4-Trimethyl-1,2-dioxetane (20):

From the kinetic data it was possible to estimate the time required for at least 90% reaction of the bromohydroperoxide 11 with base under

TABLE I

Rate of Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11)
[0.0449 M] at 0° with Sodium Hydroxide [0.0433 M] in 5:1
Methanol-water.

time (sec)	$[Br^{\ominus}]=x$	d-x	$(d-x)^{-1}$
840	4.00×10^{-3}	4.01×10^{-2}	24.9
1260	4.99×10^{-3}	3.91×10^{-2}	25.6
2280	7.28×10^{-3}	3.68×10^{-2}	27.2
3540	8.98×10^{-3}	3.51×10^{-2}	28.5
4800	11.5×10^{-3}	3.26×10^{-2}	30.7
6960	14.2×10^{-3}	2.99×10^{-2}	33.4
8940	16.6×10^{-3}	2.75×10^{-2}	36.4
10800	18.8×10^{-3}	2.53×10^{-2}	39.5
12600	20.4×10^{-3}	2.37×10^{-2}	42.2

$d = 4.41 \times 10^{-2}$ M, k_2 (graphical) $= 1.40 \times 10^{-3}$ liter mole^{-1} sec^{-1}.

TABLE II

Rate of Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11)
[0.0449 M] at 0° with Sodium Hydroxide [0.0866 M] in 5:1
Methanol-water.

time (sec)	$[Br^\ominus] = x$	$\log \dfrac{b(a-x)}{a(b-x)}$	k_2 (graphical) liter mole^{-1} sec^{-1}
1140	0.70×10^{-2}	-0.0376	
2400	1.20×10^{-2}	-0.0711	
3540	1.53×10^{-2}	-0.0975	
5460	2.01×10^{-2}	-0.142	1.39×10^{-3}
7140	2.37×10^{-2}	-0.188	
9600	2.79×10^{-2}	-0.252	
11400	2.98×10^{-2}	-0.291	
12540	3.12×10^{-2}	-0.322	

TABLE III

Rate of Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) [0.0449 M] at 0° with Sodium Hydroxide [0.130 M] in 5:1 Methanol-water.

time (sec)	$[Br^{\ominus}] = x$	$\log \dfrac{b(a-x)}{a(b-x)}$	k_2 (graphical) liter mole^{-1} sec^{-1}
540	0.58×10^{-2}	-0.0410	
840	0.74×10^{-2}	-0.0526	
1800	1.27×10^{-2}	-0.100	
3780	2.07×10^{-2}	-0.192	1.28×10^{-3}
6120	2.70×10^{-2}	-0.297	
9240	3.32×10^{-2}	-0.441	
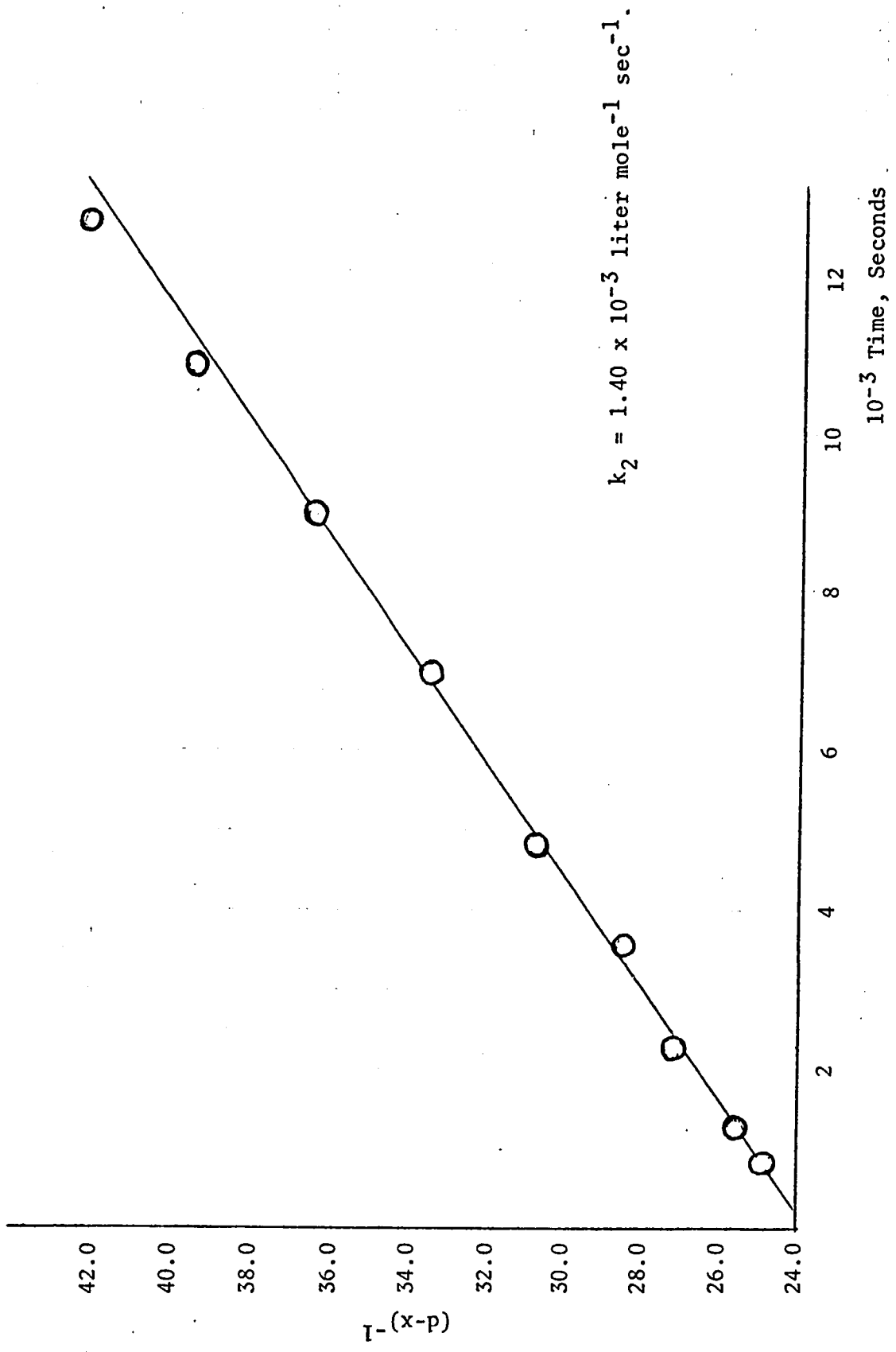
Figure 1. The reaction between 3-bromo-2-methyl-2-butyl hydroperoxide (11) [0.0449 M] and sodium hydroxide [0.0433 M] in 5:1 methanol-water at 0°.
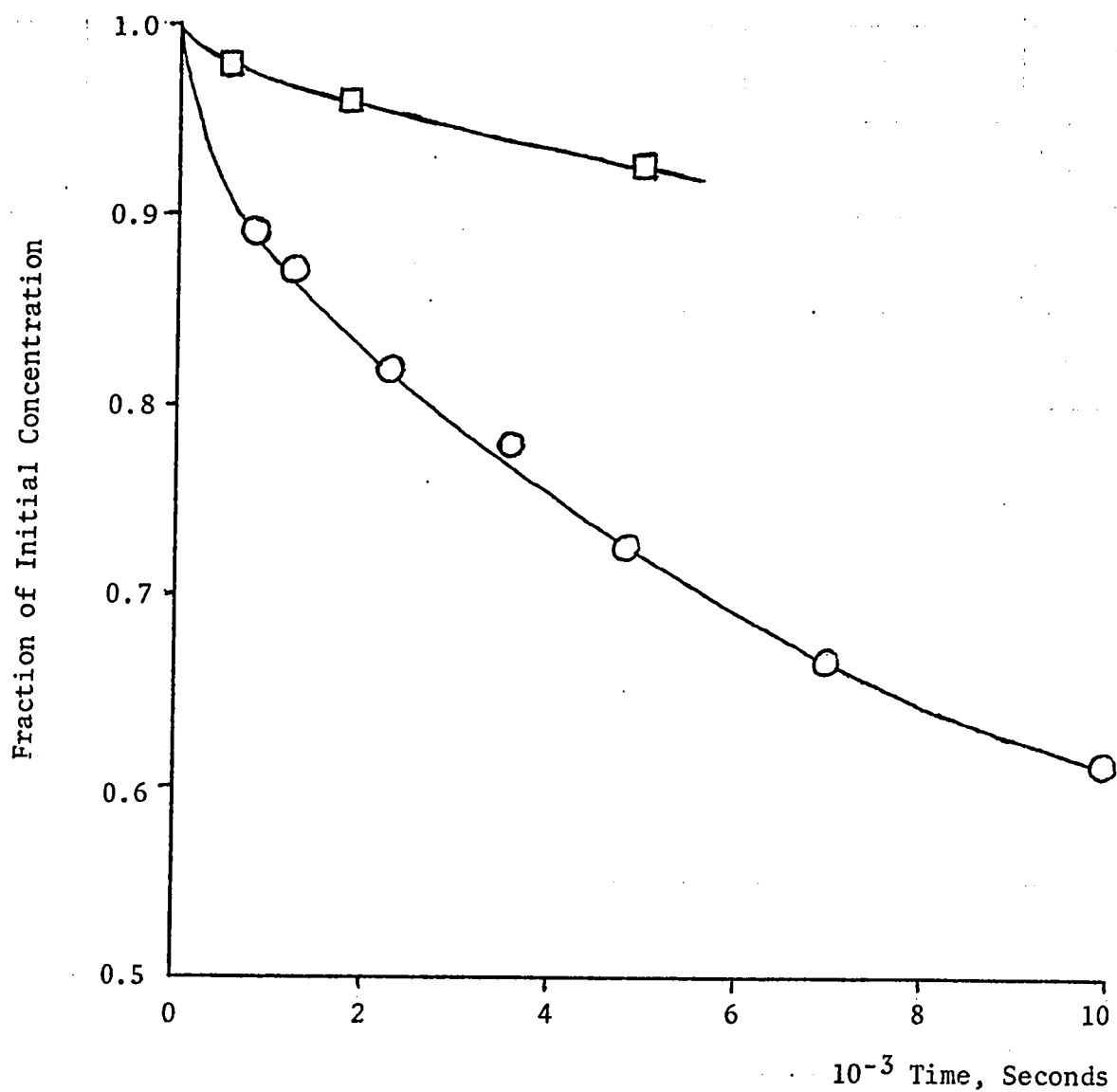
Figure 2. The reaction between 3-bromo-2-methyl-2-butyl
hydroperoxide (11) [0.0449 M] and sodium
hydroxide [0.0433 M] in 5:1 methanol-water at 0°.
□, total peroxide; ○, organic bromine.

a given set of conditions. For example, in a preparative run, when both reactants were present in ca. 1 M concentration, use was made of equation [22] (37c), where C_0 is the initial concentration of

[22]
$$\frac{1}{C_t} - \frac{1}{C_0} = k_2t$$

equimolar reactants, in this case 1.0 M, t is the time taken for C_0 to fall to C_t, and k_2 is the measured second order rate constant. For 90% reaction, C_t becomes equal to 0.1 M, giving a time, t, of ca. 110 minutes. Extraction of 20 after this time would only remove small amounts of 11. Most of the long-term reaction products such as acetone, acetaldehyde, 2,3-epoxy-2-methylbutane (13) and 2-methyl-2,3-butanediol (14) would be very water soluble and either very volatile (acetone, acetaldehyde), or non-volatile (2-methyl-2,3-butanediol). The volatility of 20 was expected to be slightly less than that of epoxide 13 and therefore, intermediate between the two extremes expected for the other reaction mixture components.

The reaction of 11 with a 10% excess of sodium hydroxide in 90% methanol-water at 0° for 110 minutes (both reactants ca. 1 M) gave a yellow solution. The mixture was diluted with an equal volume of water and extracted once with an equal volume of carbon tetrachloride or benzene. The n.m.r. spectrum of the resulting yellow extract showed that 11 had largely reacted. The n.m.r. spectra of the starting material 11 and of an extract obtained after only 45 minutes reaction of 11 with base are shown in Figures 3a and 3b, respectively. The solution of crude 20 obtained by extraction after 110 minutes

Figure 3a. Nuclear magnetic resonance spectrum of 3-bromo-2-methyl-2-
butyl hydroperoxide (11) in carbon tetrachloride.

Figure 3b. Nuclear magnetic resonance spectrum of a carbon tetrachloride
extract from the mixture obtained by reacting 3-bromo-2-
methyl-2-butyl hydroperoxide (11) [ca. 1.0 M] with sodium
hydroxide [ca. 1.0 M] in 90% methanol-water for 45 minutes
at 0°.

Figure 3c. Nuclear magnetic resonance spectrum of a solution of
3,3,4-trimethyl-1,2-dioxetane (20) in carbon tetrachloride.

Figure 3d. Nuclear magnetic resonance spectrum of a solution of
2,3-epoxy-2-methylbutane (13) in carbon tetrachloride.

3a

$$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{O-OH}{|}}{C}}-\underset{\underset{Br}{|}}{CH}-CH_3$$

3b

$$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{O-OH}{|}}{C}}-\underset{\underset{Br}{|}}{CH}-CH_3 + NaOH-CH_3OH$$

0°, 45 min., then CCl₄ ext.

3c

$$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{O-O}{|\ \ |}}{C}}-CH-CH_3$$

Low temp. dist. of CCl₄ extract

3d

$$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{O}{/\backslash}}{C}}-CH-CH_3$$

20 30 40 50 60 70 80 90 10
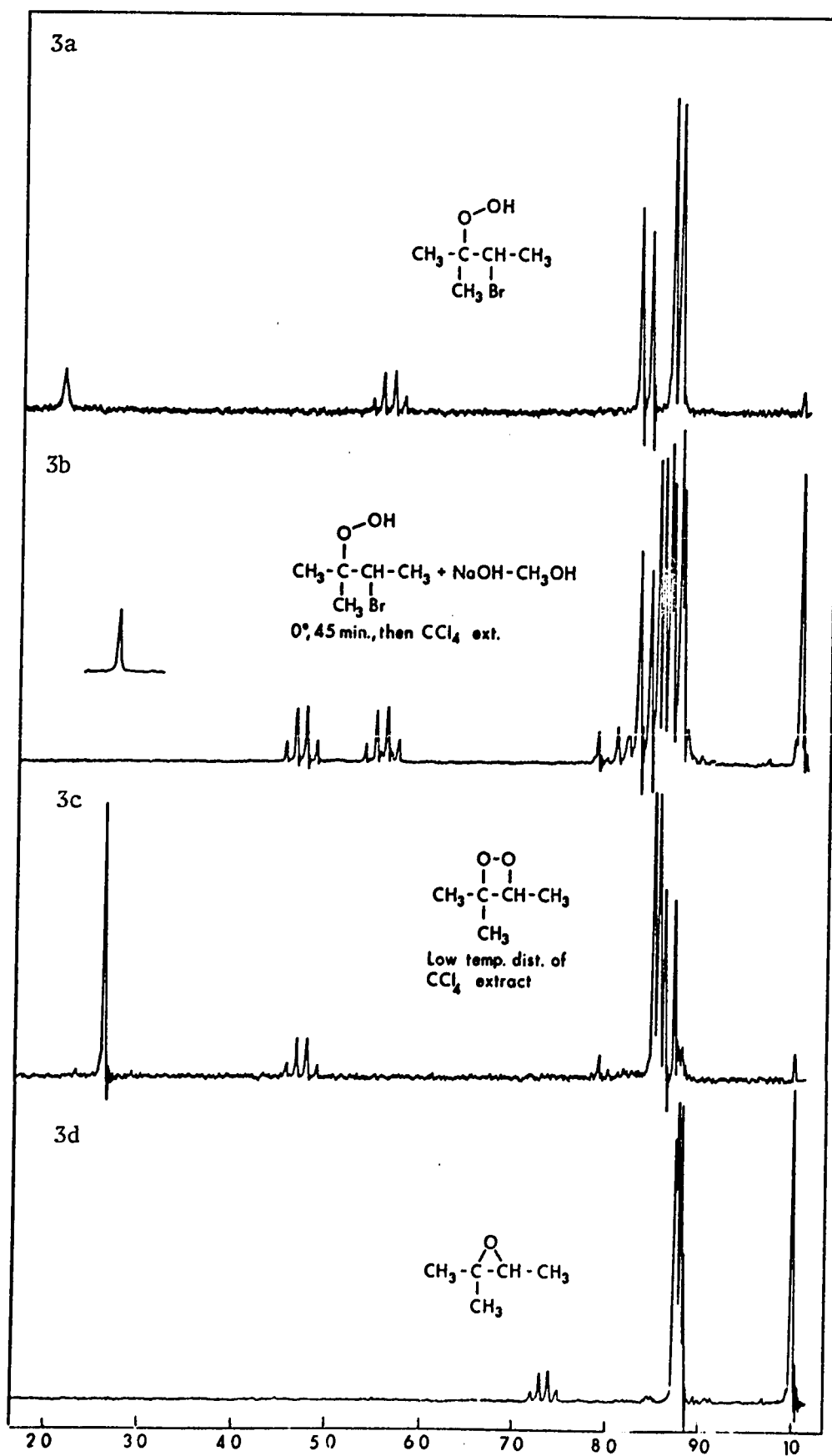
reaction was purified and concentrated by two bulb-to-bulb distillations. The n.m.r. spectrum (CCl_4) of the concentrate, given in Figure 3c, shows the features expected for 20. The spectrum showed peaks at τ 4.80 (quartet, J = 6.5 c.p.s.) due to the methine proton, τ 8.51 (singlet) and τ 8.56 (singlet) due to the non-equivalent gem-dimethyl groups, and τ 8.68 (doublet, J = 6.5 c.p.s.) of the other methyl group of 20. The relative peak areas were 1.00:10.17. For comparison purposes, the n.m.r. spectrum (CCl_4) of 2,3-epoxy-2-methylbutane (13) is included in Figure 3d.

The solutions of 20 so obtained were always yellow in color, and the n.m.r. spectra always showed trace absorptions in the region τ 8.75-9.0. The observed peak area-ratio was only slightly greater than the expected ratio of 1:9 so that impurities would be unlikely to interfere with subsequent experiments. The infrared spectrum (CCl_4) of 20, showed no absorption due to hydroxyl or carbonyl groups. The important bands were at 1370 and 1360 cm^{-1}, due to the gem-dimethyl groups; 1202 and 1156 cm^{-1}, attributable to C-O stretching bands; and 886 cm^{-1} which may be due to the O-O stretching frequency.

The yield of 3,3,4-trimethyl-1,2-dioxetane (20) was estimated by iodometric titration to be 7-12% in a number of preparations of purified concentrate. An attempt to separate 20 from unreacted 11, by chromatography of the carbon tetrachloride solution on neutral alumina, resulted in the solvent boiling on the column.

Reduction of 3,3,4-Trimethyl-1,2-dioxetane (20):

Several attempts were made to reduce the 1,2-dioxetane 20 to the corresponding glycol, 2-methyl-2,3-butanediol (14), using a variety

of methods.

a) <u>Hydrogenation</u>

It was anticipated that hydrogenation of <u>20</u> would lead to the glycol <u>14</u>, eq. [23].

$$
[23] \quad
\begin{array}{c}
O-O \\
| \quad | \\
CH_3 - C - C - H \\
| \quad | \\
CH_3 \; CH_3
\end{array}
\quad \xrightarrow{\;H_2, \; Pd.\;} \quad
\begin{array}{c}
HO \quad OH \\
| \quad | \\
CH_3 - C - C - H \\
| \quad | \\
CH_3 \; CH_3
\end{array}
$$

<center><u>20</u>   <u>14</u></center>
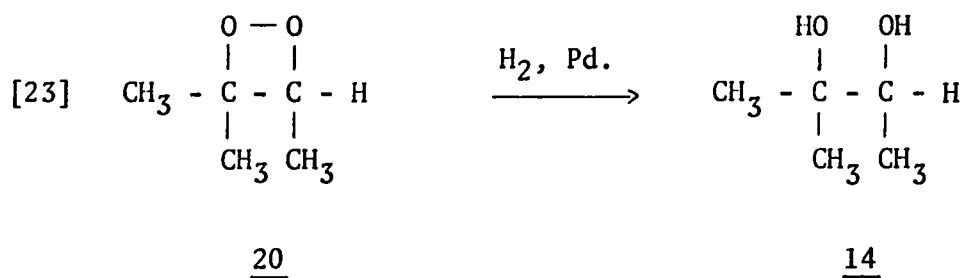
A solution of <u>20</u> in carbon tetrachloride slowly took up hydrogen at one atmosphere pressure when stirred with palladium-on-charcoal. When the slow uptake of hydrogen had ceased the mixture was filtered and concentrated. Only a trace of residue remained. The n.m.r. spectrum of the residue did not resemble that of authentic <u>14</u>, and was unexpectedly complex. As described below, a later experiment showed that palladium-on-charcoal catalyzes the decomposition of <u>20</u>.

When a solution of <u>20</u> in carbon tetrachloride was allowed to stand overnight at 0° in the presence of palladium-on-charcoal, complete decomposition occurred. N.m.r. analysis of the resulting solution showed that acetone and acetaldehyde were the only reaction products. A crude estimate of the rate of catalyzed decomposition was obtained from a second experiment. When 0.5 ml of <u>ca.</u> 0.1 M <u>20</u> in carbon tetrachloride was shaken at room temperature with 2 mg of palladium-on-charcoal in a sealed tube, the rate of decomposition of <u>20</u> was increased by some five times over the rate of thermal decomposition at room temperature. The rate of decomposition

was assessed, assuming first order kinetics, from the n.m.r. spectrum which showed that ca. 15% of the peroxide had decomposed within 45 minutes. The reaction is summarized in equation [24].

$$
[24] \quad
\begin{array}{c}
\quad\; O - O \\
\quad\; | \quad | \\
CH_3 - C - C - H \\
\quad\; | \quad | \\
\quad\; CH_3 \; CH_3
\end{array}
\quad \xrightarrow{\;Pd\;} \quad
\begin{array}{c}
O \\
\| \\
C \\
/\ \backslash \\
CH_3 \quad H
\end{array}
\quad + \quad
\begin{array}{c}
O \\
\| \\
C \\
/\ \backslash \\
CH_3 \quad CH_3
\end{array}
$$
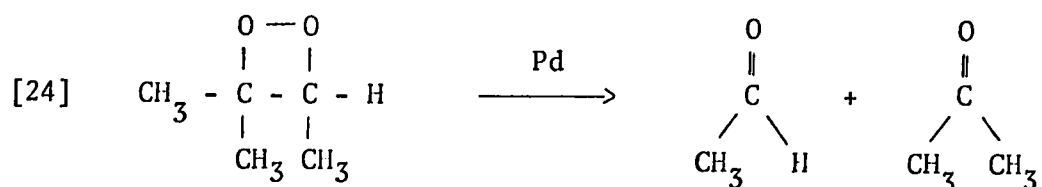
20

b) Reduction with Sodium Sulfite

It is well known that peroxides and hydroperoxides can often be reduced with neutral aqueous sodium sulfite (11). Since the reaction conditions are very mild it was decided to attempt the reduction of 20 by this method.

A solution of 20 in carbon tetrachloride was reduced by stirring with an equimolar quantity of sodium sulfite dissolved in an equal volume of water at 0°. The aqueous layer became progressively alkaline so 10% aqueous hydrochloric acid was added at intervals to maintain a pH of 7-9. When all the peroxide had been consumed the organic layer was separated. The infrared and n.m.r. spectra of the organic layer were identical with those of an authentic specimen of 2,3-epoxy-2-methylbutane (13).

The aqueous layer was treated with hydrochloric acid and barium chloride to give barium sulfate in 70% yield (based on the peroxide content of the initial solution of 20). The reaction is summarized by equation [25].

[25]

```
        O — O                              O    O - SO₃ ⊖
        |   |                              ‖    |
  H  -  C - C - CH₃     SO₃ ⊖        H  -  C  - C - CH₃
        |   |          ─────────→         |    |
        CH₃ CH₃                           CH₃  CH₃

         20
                           O
                          / \
        ─────────→  CH₃ - C - C - H      +    SO₄ ⊖
                          |   |
                          CH₃ CH₃

                           13
```
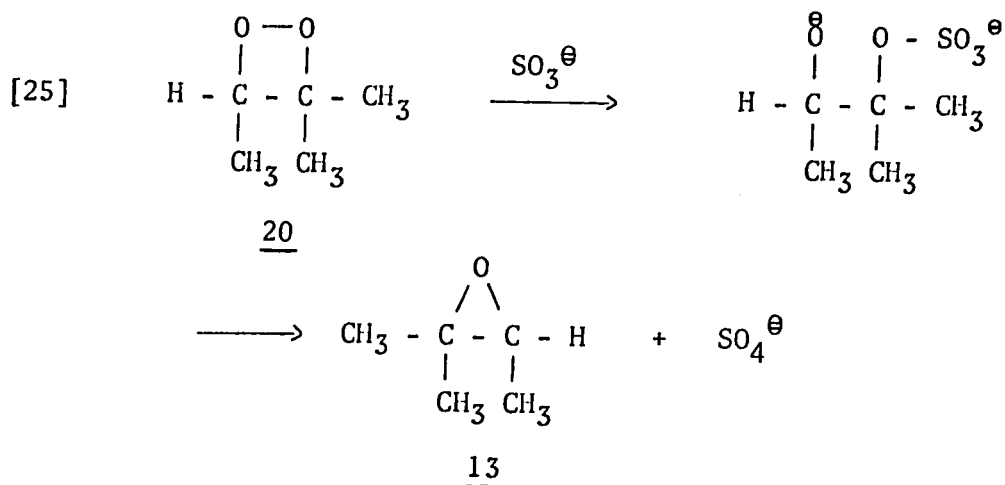
c) <u>Reduction with Acidified Potassium Iodide.</u>

The reduction of peroxidic compounds with acidified potassium iodide is a general reaction which leads to the formation of alcohols (30). The 1,2-dioxetane, 20, reacted rapidly with this reagent but isolation of small amounts of a glycol from a partially aqueous reaction mixture promised to be a difficult operation..

A solution of 20 in carbon tetrachloride was allowed to react for 15 minutes at room temperature with potassium iodide in aqueous acetic acid. The resulting mixture was freed of iodine by titration with aqueous sodium thiosulfate and then neutralized by adding solid sodium carbonate. The slurry obtained was shaken for one hour with each of four 25 ml portions of ether. The ether extracts were combined by decantation from the slurry and then dried. The ether was completely removed by repeated evaporation of the extracts with added carbon tetrachloride. A known weight of toluene was then added to the residue as internal standard and the n.m.r. spectrum (CCl_4) recorded. The n.m.r. spectrum was identical with that of an authentic sample of the glycol 14. The yield of 14, 50%, was estimated by

integrating the methyl groups of toluene and the glycol, and relating the area-ratio to the known weight of the added toluene.

Thermal Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20)

In Chapter I, evidence was presented to suggest that 20 and other 1,2-dioxetanes should undergo facile decomposition to give carbonyl compounds. To clarify the literature on this point it was decided to make a study of the decomposition of 20 in carbon tetrachloride solution.

Solutions of 20 in carbon tetrachloride, were decomposed in sealed n.m.r. tubes by heating at 60° for 12 hours. During decomposition, all the peaks due to 20 disappeared and new absorption appeared at τ 0.20 (quartet, J = 2.9 c.p.s.) due to the aldehydic proton of acetaldehyde, τ 7.82 (doublet, J = 2.9 c.p.s.) due to the methyl group of acetaldehyde, and τ 7.88 (singlet) due to the methyl groups of acetone. The relative peak areas were 1.0:8.8; required 1.0:9.0. The spectrum was matched by that of a synthetic, equimolar mixture of acetone and acetaldehyde.

In order to measure the yield of cleavage products in the reaction, the experiment was repeated with benzene added as internal standard. Under these conditions the methyl group absorptions of the products were not resolved. From the relative peak areas of the methyl group absorption of 20 and benzene before decomposition, and the relative peak areas of the methyl group absorption (acetone and acetaldehyde) and benzene after decomposition, the product balance was found to be 93%. G.l.c. analysis confirmed the presence of acetone and acetaldehyde. This result establishes the empirical formula of 20

as being $C_5H_{10}O_2$.

Rates of Thermal Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20):

Solutions of 20 in carbon tetrachloride were decomposed by heating in a thermostatted bath. After at least 15 minutes immersion the clock was started. At suitable time intervals samples were withdrawn by pipette, quickly weighed, and estimated for peroxide content by iodometric titration. A small residual titer was observed at the completion of each run which was due to impurities and the blank titration. Each titer was corrected for constant weight of sample and for the residual titer. In a trial experiment using 3-bromo-2-methyl-2-butyl hydroperoxide (11), added acetone had no effect on the peroxide titer. The reaction exhibited first order kinetics during 2-3 half-lives. The rate constants for the first order decomposition of 20 were estimated graphically using the formula of equation [26] (37d).

$$[26] \qquad\qquad -\ln \frac{a-x}{a} = k_d t$$

By plotting the left side of equation [26] versus the time, a straight line was obtained whose slope gave the rate constant k_d. An example of the data obtained for decomposition of 20 at 50.2°, is shown in Table IV. First order plots of the data obtained at four temperatures, 40.2°, 50.2°, 55.3° and 60.8° are shown in Figure 4. The rate constants, k_d, obtained from these graphs are given in Table V. Only one decomposition was studied at each temperature because the solutions of 20 used, were known to be impure. For this reason further experimentation and/or a sophisticated treatment of the data was felt

TABLE IV

Rate of Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20), [0.07 m]

in Carbon Tetrachloride at 50.2°.

time (seconds)	[20]	$\frac{a-x}{a}$	$-\ln\frac{a-x}{a}$
-1000	0.0700 m	-	-
0	0.0578 m	1.0	0
1620	0.0434 m	0.752	0.285
3800	0.0301 m	0.520	0.654
7140	0.0185 m	0.319	1.14

k_d (graphical) = 1.66 x 10^{-4} sec^{-1}.
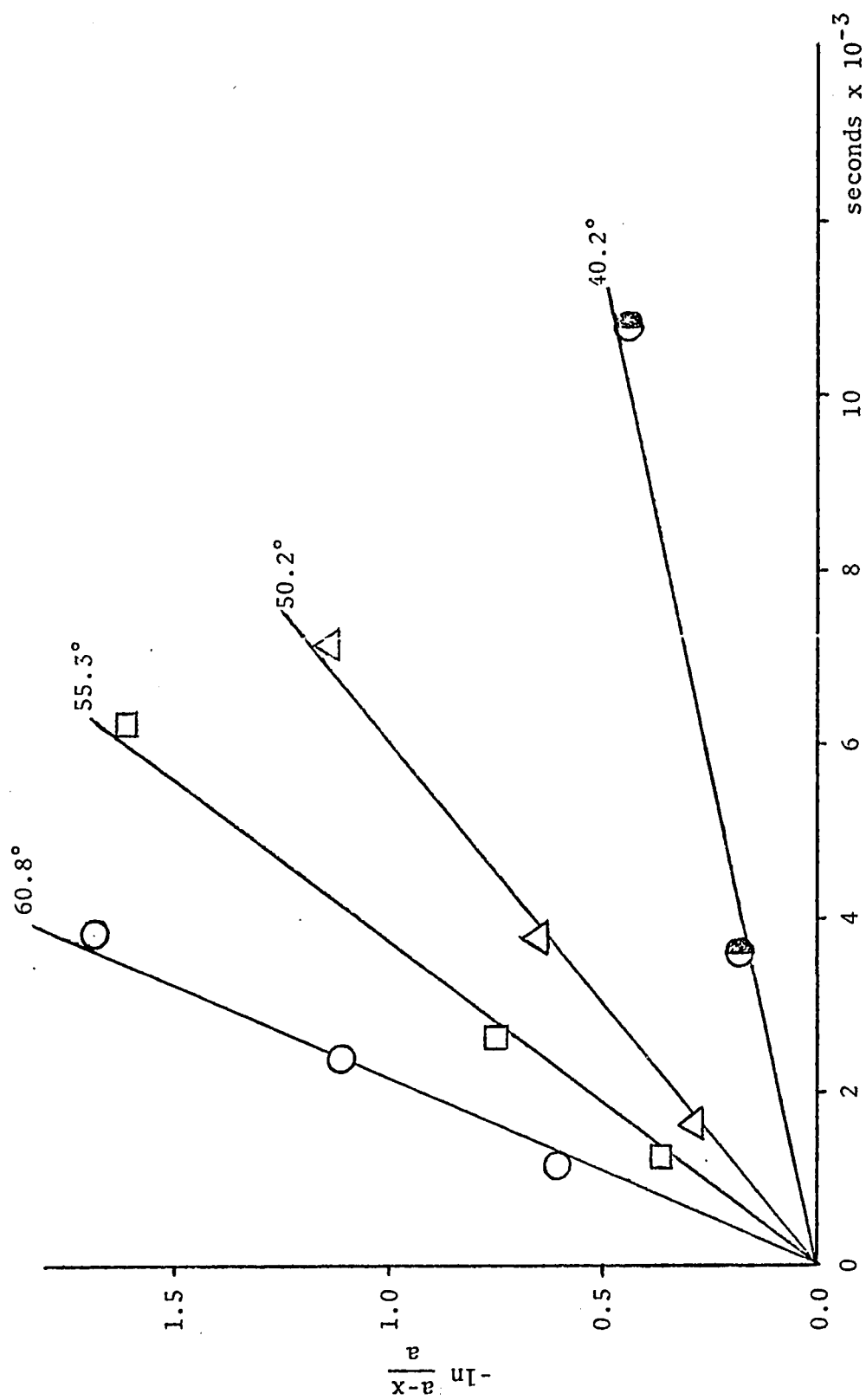
Figure 4. The rate of thermal decomposition of 3,3,4-trimethyl-1,2-dioxetane (20) in carbon tetrachloride.

TABLE V

Thermal Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20).

Solvent	Analysis	Temperature	Rate Constant sec^{-1}
Carbon tetrachloride	Titrimetric	60.8°	4.63×10^{-4}
Carbon tetrachloride	Titrimetric	55.3°	2.69×10^{-4}
Carbon tetrachloride	Titrimetric	50.2°	1.66×10^{-4}
Carbon tetrachloride	Titrimetric	40.2°	4.42×10^{-5}
Carbon tetrachloride	N.m.r.	36°	2.9×10^{-5}
Carbon tetrachloride	Estimated	36°	2.9×10^{-5}

to be unwarranted.

From the rate data of Table V and equation [27] (37e)

$$[27] \qquad \log k_1 = \log A - \frac{E_a}{2.303 \ RT}$$

the activation energy, E_a, and the frequency factor, A, were determined to be 22.9 kcal $mole^{-1}$, and 2.3×10^{-12} sec^{-1}, respectively (Figure 5). The enthalpy of activation, $\Delta H^{\ddagger}$, was calculated from equation [28] (38) to be 22.3 kcal mole at 50°.

$$[28] \qquad \Delta H^{\ddagger} = E_a - RT$$

The entropy of activation, $\Delta S^{\ddagger}$, was calculated from equation [29] (38).

$$[29] \qquad \frac{\Delta S^{\ddagger}}{4.576} = \log k_d - 10.753 - \log T + \frac{E_a}{4.576 \ T}$$

Using either of the rate constants obtained at 40.2° and 60.8°, the entropy of activation for the reaction was found to be 7 e.u.

The thermal decomposition of 20 in carbon tetrachloride was also studied by n.m.r. spectroscopy using benzene as internal standard. A solution of 20 in carbon tetrachloride was allowed to decompose in an n.m.r. tube which was held in the probe of the n.m.r. spectrometer. The spectral changes which occurred are shown in Figure 6. The rate of reaction was measured by studying the increase in methyl group absorption of the products relative to that of added benzene. The result, given in Table V is in agreement with the extrapolated titrimetric rate.

Figure 5. The activation energy for the thermal decomposition of 3,3,4-trimethyl-1,2-dioxetane in carbon tetrachloride.

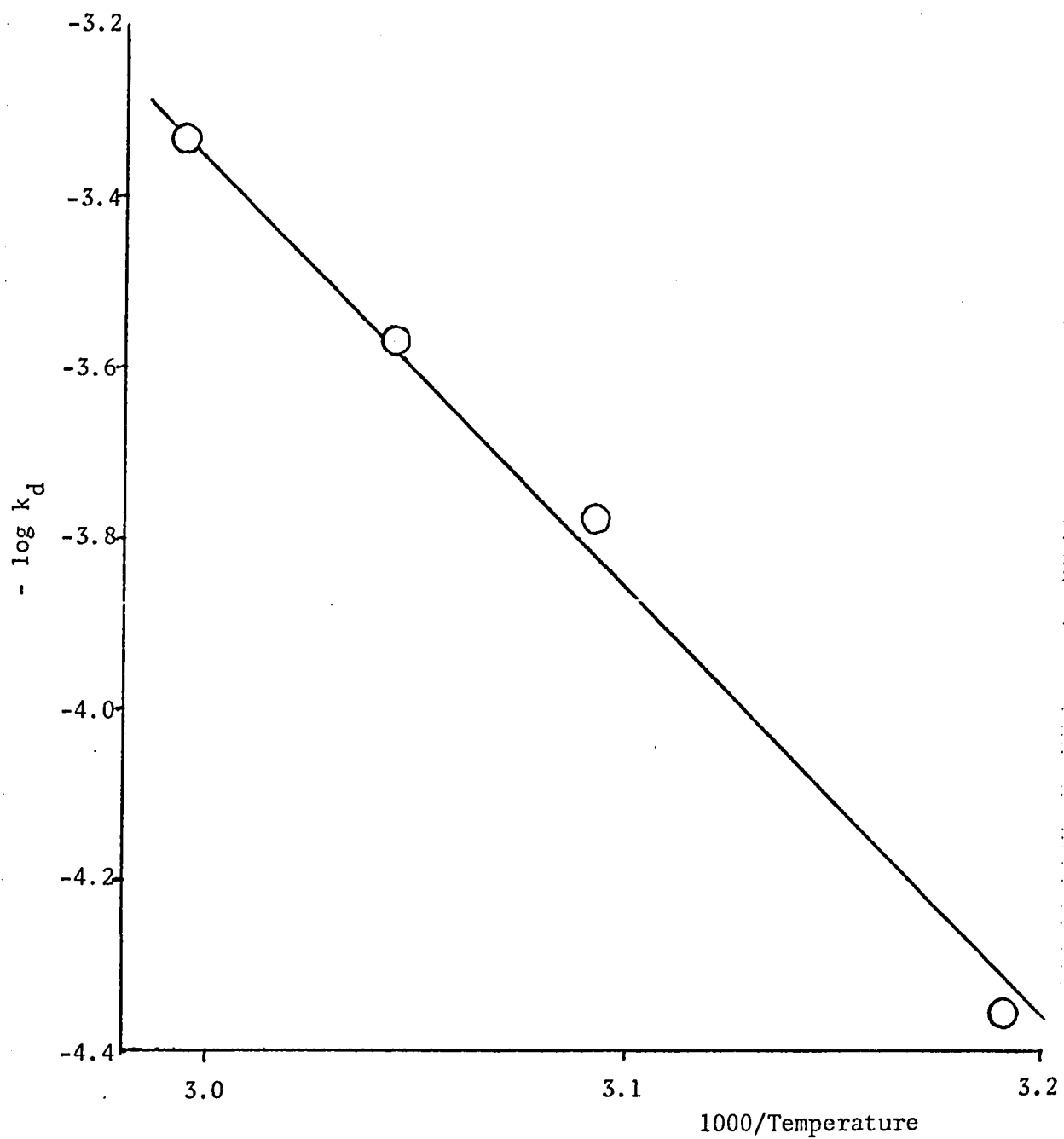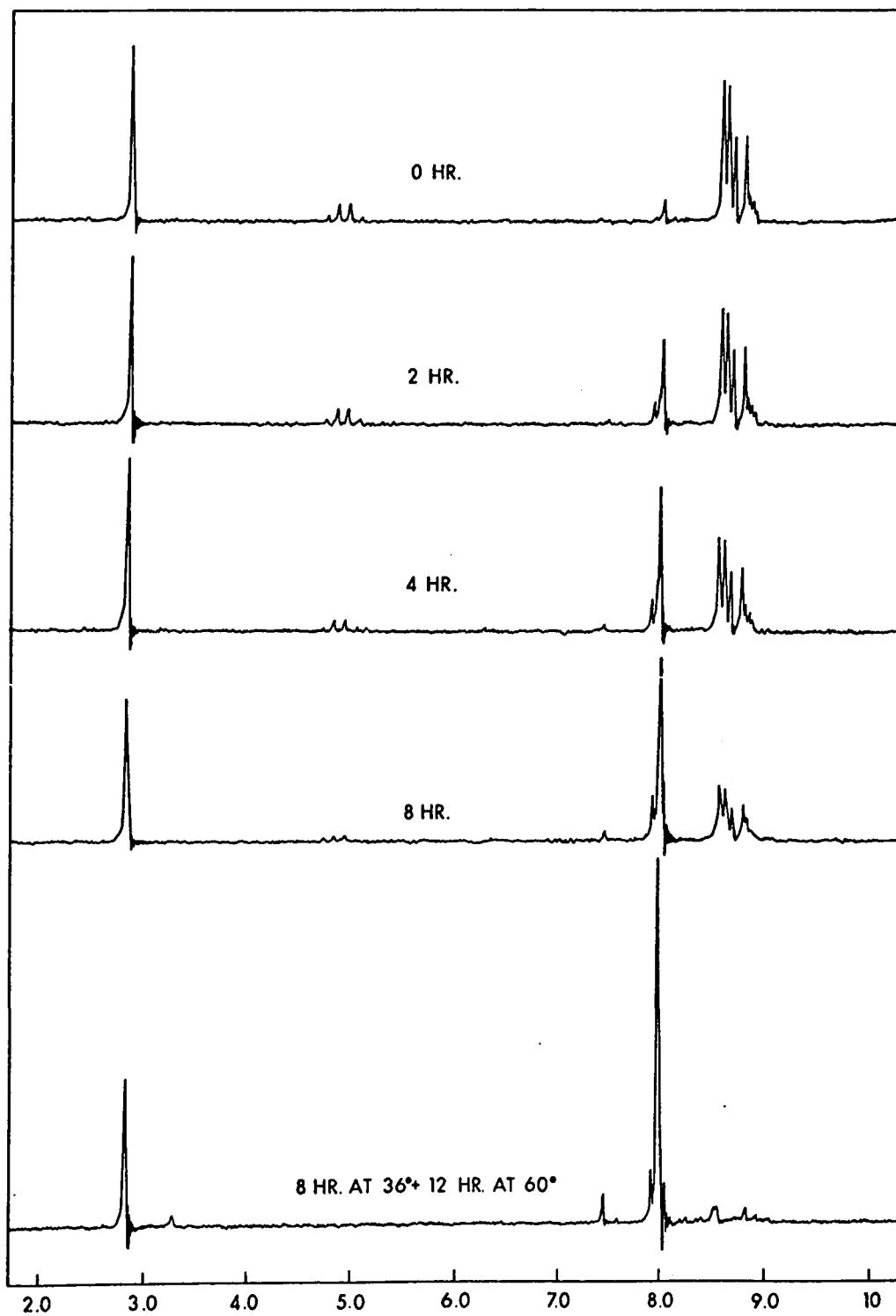Figure 6. Nuclear magnetic resonance spectra obtained during the thermal decomposition of 3,3,4-trimethyl-1,2-dioxetane (20) in carbon tetrachloride solution with benzene as internal standard.

Luminescence in the Thermal Decomposition of 3,3,4-Trimethyl-1,2-
dioxetane (20):

A proposal has recently been made in which it is suggested that
the thermal decomposition of four-membered cyclic peroxides should be
accompanied by the emission of light (39). The suggestion, based on
orbital symmetry arguments, was made to account for many instances of
chemiluminescence and bioluminescence (39) because 1,2-dioxetanes were
thought to be involved in these processes. Having obtained 20, the
first such compound to be isolated, it was decided to test this
interesting postulate.

In agreement with this postulate a faint bluish luminescence was
observed when a benzene solution of 20 was heated above 70° in the
dark. Crude emission spectra were obtained by decomposing benzene
solutions of 20 at 60° in a water-jacketed, 10 cm polarimeter tube
fitted with a quartz window. The spectra were scanned manually using
a Bausch and Lomb 500 mm monochrometer in conjunction with an R.C.A.
1 P28 photomultiplier tube. The emission intensity was corrected for
photomultiplier response in accord with the manufacturer's specifications.
Each spectrum was recorded at 10 mμ intervals, and appeared as a series
of steps on the recorder chart paper. The position of the maximum
appeared to shift during a run so spectra were recorded as rapidly as
possible. Spectra were obtained using benzene solutions containing 20
at 0.21 M, 0.021 M and 0.0021 M concentration. The spectra obtained
using 0.21 M and 0.021 M solutions of 20 are shown in Figure 7.

McCapra has predicted (39) that the carbonyl compounds produced
in the decomposition of 20 should be in singlet electronic states with

Figure 7. Luminescence Spectra of 3,3,4-Trimethyl-1,2-dioxetane (20).
Decomposition at 60°.
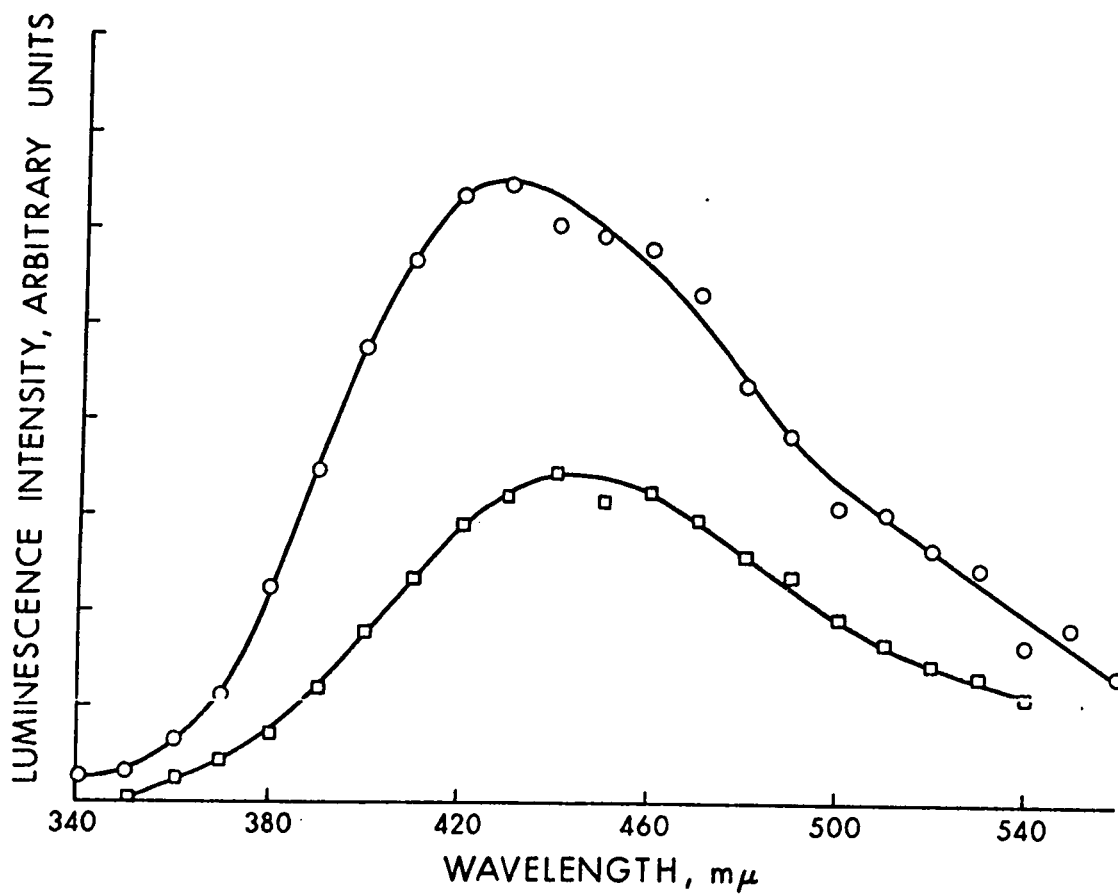
Initial Concentrations

□, 0.21 M 20; O, 0.021 M 20.

(The two curves are not on the same scale).

one of the fragments in an excited state. If this were the case it should be possible to perform many of the photochemical reactions of carbonyl compounds.

Apart from those photochemical reactions where the initially excited species is directly involved, there are a large number of reactions in which energy is transferred from the initially excited molecule to a second substance which then undergoes a subsequent reaction. If it could be shown that the excited carbonyl compound generated during the decomposition of 20 was capable of transferring its energy to a suitable acceptor, then it would follow that 20 could be used as a source of energy in a wide variety of photochemical reactions. As described below, it was possible to demonstrate that energy transfer occurred from both the excited singlet and triplet state of one of the carbonyl compounds produced during the thermal decomposition of 20.

. Significantly increased intensities and changes in the color of the luminescence were observed during the decomposition of 20 containing added anthracene (violet), pyrene (turquoise) or napthacene (green). The same colors were produced when benzene solutions of these added compounds were irradiated with ultraviolet light. These results show that the excited carbonyl fragments from the decomposition of 20 are produced in singlet states. If the excited molecules produced were in triplet states, no energy transfer would be possible because the triplets would be quenched by the oxygen of the air dissolved in the solution (40). Intense green emission was also observed when a degassed benzene solution of 20 was decomposed in the presence of

biacetyl. A degassed solution 0.104 M in 20 and 0.2 M in biacetyl contained in a sealed tube was heated to 70° by immersion in a hot water bath. The brilliant green glow which resulted was very much brighter than that of a similar sample lacking biacetyl. In a further experiment 0.002 M biacetyl was used and again the green glow was much brighter than that of a sample lacking biacetyl. During chemiluminescence all the solutions appeared to be turbid, which gave a whitish appearance to the colors, but in reality the solutions were perfectly free of suspended matter.

The increased intensities observed in the energy transfer experiments were not due to induced decomposition of 20 by the quenching agent. For example, the first order rate constant, k_d, for decomposition of 20 (0.22 M in benzene) is 5.5 x 10^{-4} sec^{-1} at 60.3°. In the presence of 0.2 M biacetyl the rate is still first order and k_d = 11.3 x 10^{-4} sec^{-1}. Although a two-fold increase in rate was observed during the decomposition of 20 in the presence of 0.2 M biacetyl, the vastly increased brightness of the luminescence under these conditions was obviously not due to the rate increase alone. In a trial experiment using 3-bromo-2-methyl-2-butyl hydroperoxide, added biacetyl had little effect on the analytical procedure for peroxide estimation other than making the use of starch indicator imperative.

DISCUSSION

The base-promoted cyclization of 3-bromo-2-methyl-2-butyl
hydroperoxide (11) to give 3,3,4-trimethyl-1,2-dioxetane (20) is
entirely analogous to the formation of epoxides in the base-promoted
reactions of β-halohydrins (41). However, this result is in sharp
contrast to the base-promoted reaction of 3-bromo-2,3-dimethyl-2-
butyl hydroperoxide (18) (4), which gives a quantitative yield of
the allylic hydroperoxide (19) eq. [14]. This contrast in behavior
is discussed in Chapter IV.

The 1,2-dioxetane, 20, is probably the first compound of this
class ever to be isolated. The facile thermal decomposition of 20
to give acetone and acetaldehyde in essentially quantitative yield,
establishes the empirical formula as $C_5H_{10}O_2$. The volatility of 20
is more in keeping with the monomeric structure 20 rather than the
dimeric structure 21.
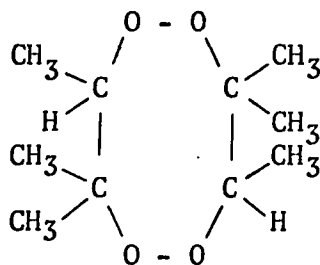
21

A molecular weight determination would have settled this question if
20 had been isolated in a pure state. A monomeric structure was

established for 3,3,4,4-tetramethyl-1,2-dioxetane (49), described in Chapter IV, which was isolated in the solid state. This latter compound was volatile and possessed similar properties to those of 20.

The reduction of 20 with potassium iodide in acetic acid solution to give 2-methyl-2,3-butanediol (14) is consistent with either a monomeric or dimeric structure, but the reduction of 20 by sodium sulfite to 2-methyl-2,3-epoxy-butane (13), is best explained in terms of a monomeric structure eq. [30].

$$[30] \quad \underset{\substack{\\ \\ 20}}{\begin{array}{c} O\!-\!O \\ | \quad | \\ CH_3-C-C-CH_3 \\ | \quad | \\ H \quad CH_3 \end{array}} \quad \xrightarrow{SO_3^{\ominus}} \quad \begin{array}{c} O \quad OSO_3^{\ominus} \\ \| \quad | \\ CH_3-C-C-CH_3 \\ | \quad | \\ H \quad CH_3 \end{array}$$

$$\longrightarrow \quad \underset{\substack{\\ \\ 13}}{\begin{array}{c} O \\ /\backslash \\ CH_3-C-C-CH_3 \\ | \quad | \\ H \quad CH_3 \end{array}} \quad + \quad SO_4^{\ominus}$$
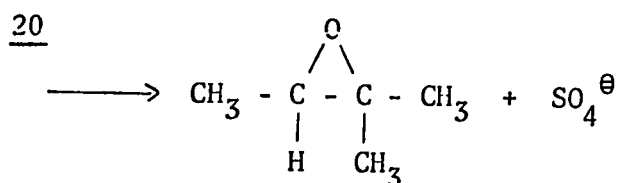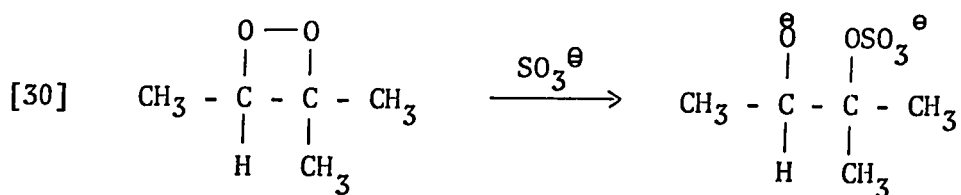
The reaction between β-hydroxy sulphates and base is known to give epoxides (42).

The enhanced rate of decomposition of 20 in the presence of palladium-on-charcoal suggests that catalyzed decomposition of 20 may also have taken place in the attempted reduction of 20 with hydrogen and palladium-on-charcoal. As discussed below such decompositions are normally expected to be thermally forbidden but it has been suggested (43,44) that noble metal catalysts are able to provide lower energy pathways for forbidden decompositions and rearrangement reactions.

The n.m.r. and infrared spectra of $\underline{20}$ show the absence of olefinic or hydroxyl absorption and are entirely consistent with the proposed structure. The low field absorption of the methine proton of $\underline{20}$ at τ 4.80 in the n.m.r. spectrum, is due to the deshielding effect of the oxygen atoms in the ring. An estimate can be made of the position of absorption of this methine proton in the n.m.r. spectrum. Cyclobutane exhibits a single resonance line in the n.m.r. spectrum at τ 8.04 (45), but the protons of oxetane appear at lower field. The α-protons of oxetane appear at τ 5.27 while the β-protons are less deshielded by the oxygen atom of the ring and appear at τ 7.28 (46). The protons of the hypothetical heterocycle, 1,2-dioxetane, would be both α and β to oxygen atoms and would be expected to be deshielded by both oxygen atoms. Compared to cyclobutane the hydrogen atoms of 1,2-dioxetane would be deshielded by an amount equal to the sum of the deshielding observed for the α- and β-protons of oxetane. Consequently, the protons of 1,2-dioxetane should absorb at τ 8.04 - τ (8.04-5.27) - τ (8.04-7.28) = τ 4.51. In the case of $\underline{20}$ the methine proton would also be deshielded by the adjacent methyl group (-0.4 p.p.m.) (47) and shielded by the two methyl groups on the β-carbon (+0.2 p.p.m.) (47), so that the position of resonance of the methine proton of $\underline{20}$ should be at τ 4.51 - 0.4 + 0.2 = τ 4.31. This value is at lower field than the observed value of τ 4.80, but serves to illustrate that the low-field absorption of the methine proton in $\underline{20}$ is by no means anomalous.

Mechanism of Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20).

In principle, the decomposition of 20 can proceed by a two-step mechanism involving initial homolytic cleavage of the oxygen-oxygen bond eq. [31], or by a one-step concerted pathway eq. [32]

$$
[31] \quad
\begin{array}{c}
O - O \\
| \quad | \\
CH_3 - C - C - CH_3 \\
| \quad | \\
CH_3 \; H
\end{array}
\xrightarrow{\Delta}
\begin{array}{c}
\dot{O} \quad \dot{O} \\
| \quad | \\
CH_3 - C - C - CH_3 \\
| \quad | \\
CH_3 \; H
\end{array}
\longrightarrow
\begin{array}{c}
O \\
\| \\
C \\
/ \; \backslash \\
CH_3 \; CH_3
\end{array}
+
\begin{array}{c}
O \\
\| \\
C \\
/ \; \backslash \\
CH_3 \; H
\end{array}
$$

20

$$
[32] \quad
\begin{array}{c}
O \quad O \\
| \quad | \\
CH_3 - C - C - CH_3 \\
| \quad | \\
CH_3 \; H
\end{array}
\xrightarrow{\Delta}
\begin{array}{c}
O \\
\| \\
C \\
/ \; \backslash \\
CH_3 \; CH_3
\end{array}
+
\begin{array}{c}
O \\
\| \\
C \\
/ \; \backslash \\
CH_3 \; H
\end{array}
$$

20
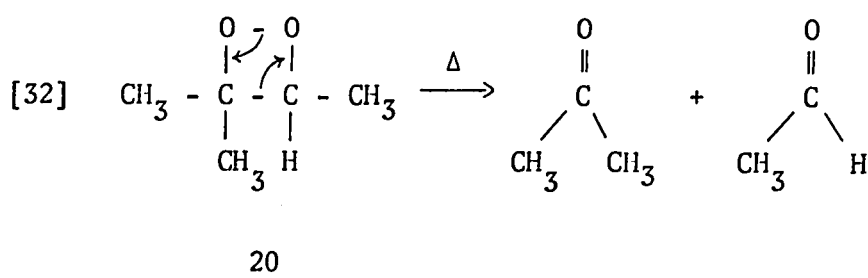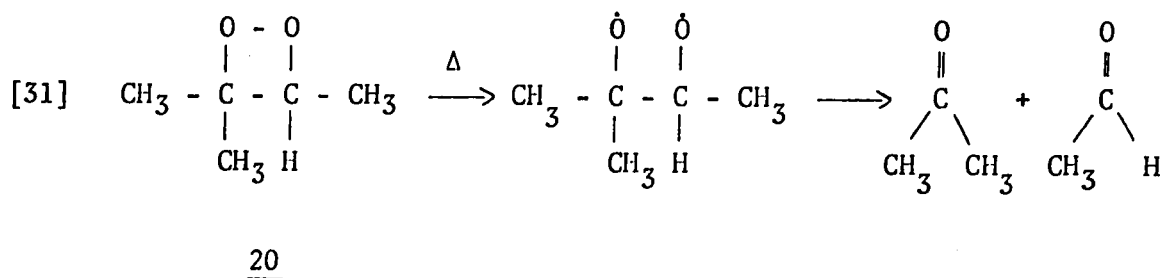
The activation energies observed for the thermal decomposition of dialkyl peroxides are usually in the range 32-37.5 kcal mole^{-1} (48). The lower activation energy, 22.9 kcal mole^{-1}, observed during the decomposition of 20, is compatible with a two-step mechanism involving homolytic cleavage of the oxygen-oxygen bond because the ring strain and torsional strain incorporated in 20 would tend to reduce the normal activation energy for oxygen-oxygen bond cleavage. The torsional strain in 20 arises from the cis-rotation barrier of hydrogen peroxide which was incorporated into 20 during its formation. The cis-rotation barrier of hydrogen peroxide has recently been found to be 7 kcal mole^{-1} (49).

If the decomposition of 20 were to occur by a one-step concerted pathway then the activation energy for this process would have to be less than the ca. 35 kcal mole^{-1} (48) observed for dialkyl peroxide decomposition, otherwise a two-step mechanism would be followed.

The entropy of activation for the decomposition of 20 was found to be 7 e.u.   Such a value implies (38f) that little change in degree of freedom occurs in proceeding from 20 to the transition state, and is consistent with either of the two mechanisms for decomposition.   As discussed later, the energy liberated during the decomposition of 20 is only sufficient to produce one excited carbonyl compound.   The production of the excited species appears to be an efficient process, so it would be surprising if all the excess energy were incorporated into one carbonyl fragment during a two-step decomposition of 20.   Consequently, it seems most probable that the decomposition of 20 proceeds by a one-step, concerted reaction.

McCapra (39) has recently suggested that if the thermal decomposition of four-membered cyclic peroxides is a concerted reaction then one of the carbonyl fragments should be formed in an excited singlet state.   However, re-examination of his theory reveals that both carbonyl fragments should be formed in excited singlet states or that one fragment should be doubly excited.   McCapra's argument is an extension of the theory of cycloaddition reactions as developed by Hoffmann and Woodward (50).   In McCapra's theory (39), the orbital symmetry arguments originally developed to explain cycloaddition reactions (50) are used in reverse (51) to predict the outcome of cyclodecomposition reactions.   This treatment (39,51) is best

understood with regard to the cyclodecomposition of cyclobutane, where it is assumed that the oxygen orbitals of 20 are equivalent to the carbon orbitals of cyclobutane for the purposes of developing symmetry arguments.

The procedure consists in the construction of correlation diagrams for the molecular orbitals involved in reaction and classifying the levels with respect to those symmetry elements which are retained throughout the reaction (50). The geometry of departure of the two ethylene molecules was assumed to be suprafacial-suprafacial in the original treatment (50,51), but other arrangements such as suprafacial-antarafacial, and antarafacial-antarafacial can be envisaged (52).

In the case of the suprafacial-suprafacial decomposition (Figure 8), the cyclobutane molecule is assumed to be planar. The form of the molecular orbitals projected upon the plane passing through the four carbon atoms of cyclobutane and of the products of decomposition is also shown in Figure 8. The orbitals are classified as symmetric (S) or antisymmetric (A) with respect to σ_1, a plane bisecting the cyclobutane molecule in a vertical direction, and σ_2, a plane bisecting the cyclobutane molecule in the horizontal direction. The lower diagram of Figure 8 shows the four reactant σ levels and the four corresponding π levels of the products. From Figure 8 it can be seen that the σ SS oribtal passes into the bonding π SS orbital, while σ AS passes into the antibonding π AS orbital, thus it may be concluded that the suprafacial-suprafacial decomposition of a cyclobutane molecule would give rise to the formation of one ground state ethylene

Figure 8. The Suprafacial-Suprafacial Decomposition of
Cyclobutane.
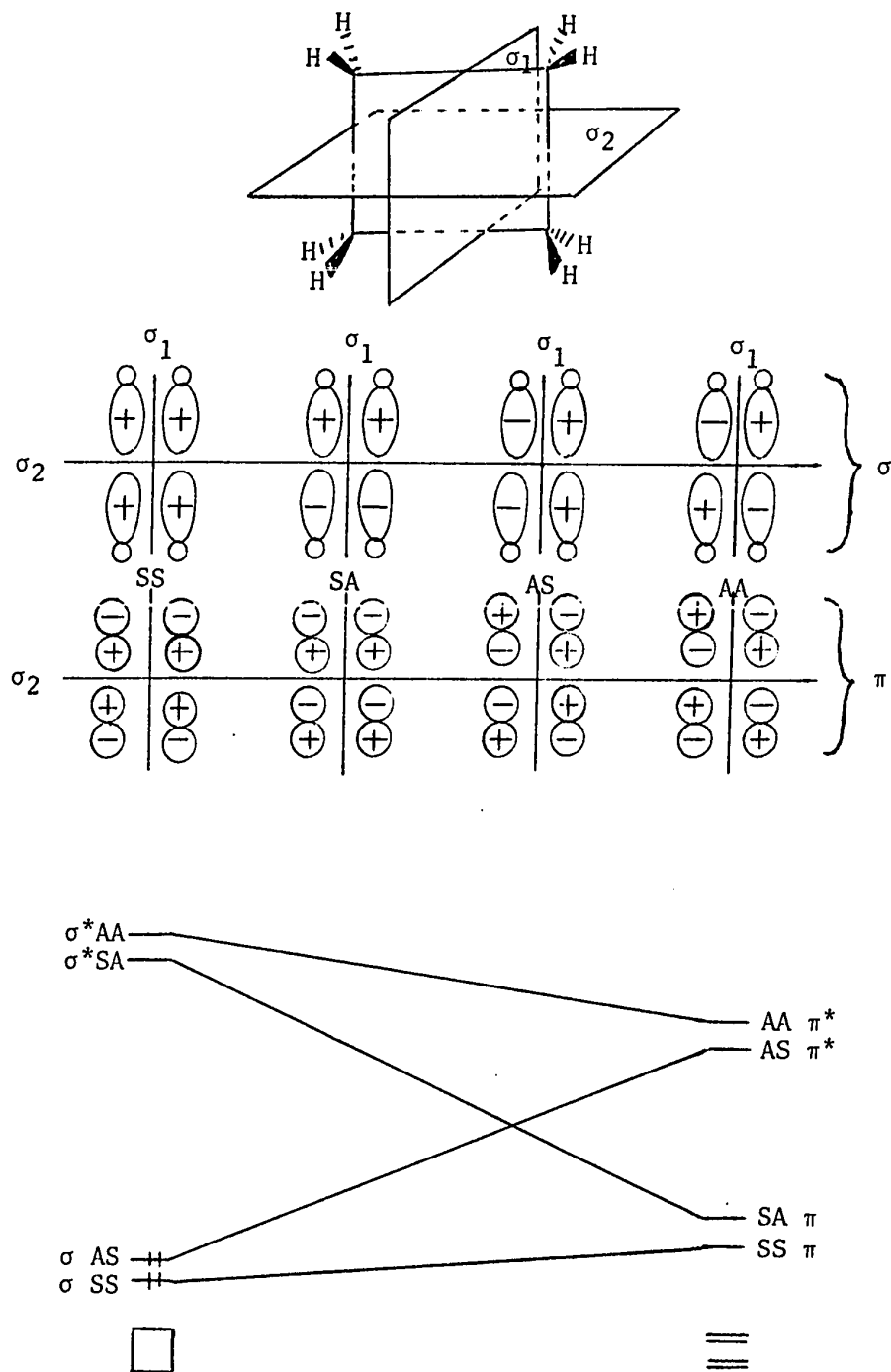
and one doubly excited molecule. Woodward has pointed out

(51) that such a process would require a large input of energy and is

unlikely to occur.

For the case of suprafacial-antarafacial decomposition the

geometries of the reactant and products are shown in Figure 9.

Throughout this mode of decomposition symmetry is maintained with

respect to a C_2 axis passing through the midpoints of the two σ bonds

which are retained in the products. Figure 9 also shows the form of

the molecular orbitals of the reactant and products classified with

respect to rotational symmetry about the C_2 axis. From this diagram

it can be seen that the reactant σ levels do not correlate with the

π orbitals of the products. Consequently, no conclusion can be drawn

regarding the fate of the ethylene molecules during the suprafacial-

antarafacial decomposition of cyclobutane.

Figure 10 shows a similar treatment for the case of antarafacial-

antarafacial decomposition of cyclobutane. Decomposition via this mode

should either lead to two electronically-excited ethylene molecules, or

give one doubly excited molecule and one non-excited. If it assumed

that the orbitals on the oxygen atoms of 20 have the same symmetries

as the carbon orbitals of cyclobutane, then it follows that the thermal

decomposition should lead to the formation of either two singly excited

carbonyl fragments, or one doubly excited fragment and one non-excited.

Some assessment can be made of the energy liberated in such

reactions, by calculating the heats of formation of reactants and

products using the additivity of group properties (53). According to

this concept every molecule is composed of irreducible groups each of

Figure 9.   The Suprafacial-Antarafacial Decomposition of
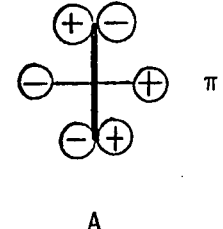   Cyclobutane
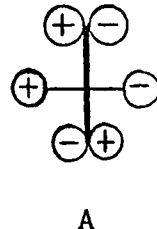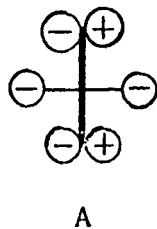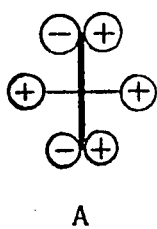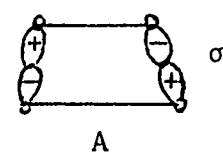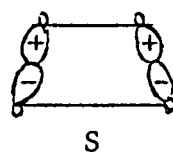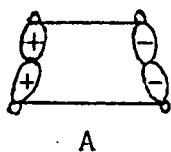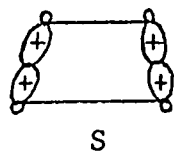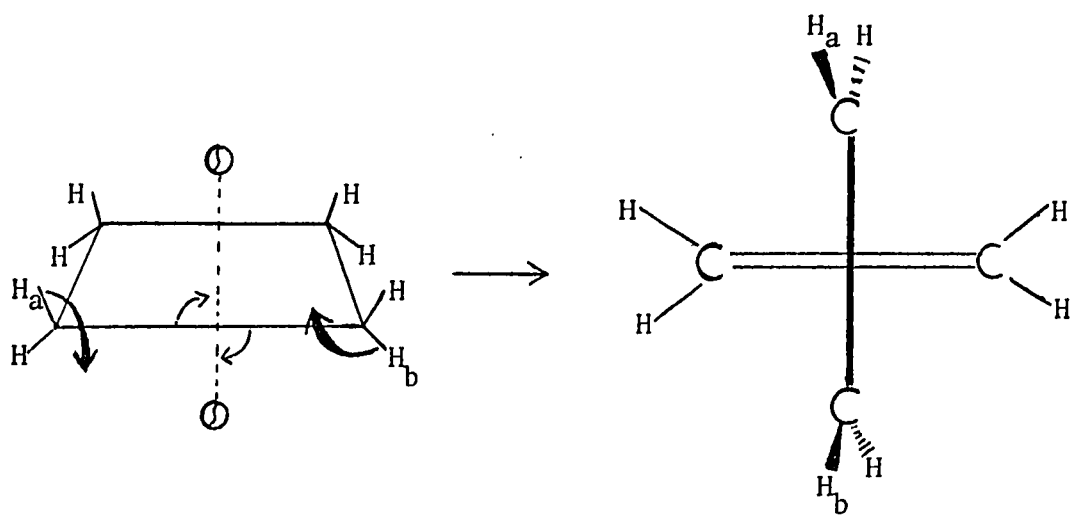
Figure 10.   The Antarafacial-Antarafacial Decomposition of
             Cyclobutane.
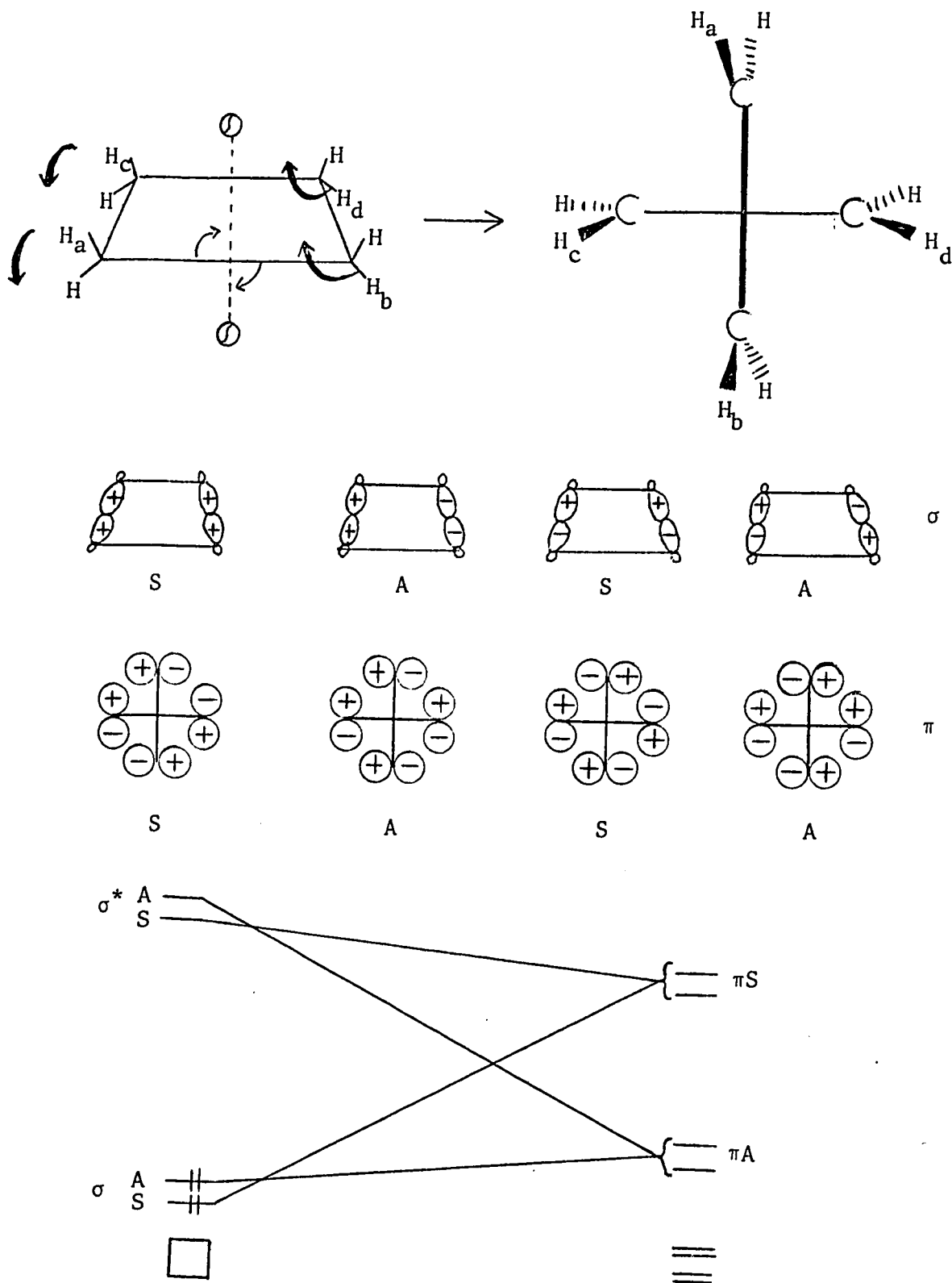
which makes a contribution to the thermodynamic parameters of the molecule. For example, compound 20 contains three methyl groups which each consist of one carbon atom bonded to three hydrogen atoms and also to another carbon atom. Of these second carbon atoms two are bonded to an oxygen atom and three carbon atoms while the third is bonded to an oxygen atom, a hydrogen atom and two carbon atoms. In turn, each of the oxygen atoms is bound to another oxygen atom and a carbon atom. Each of these arrangements constitutes an irreducible group. Using the nomenclature of Benson (53), compound 20 is

$$
\begin{array}{c}
\text{O} - \text{O} \\
| \quad | \\
\text{CH}_3 - \text{C} - \text{C} - \text{CH}_3 \\
| \quad | \\
\text{CH}_3 \quad \text{H}
\end{array}
$$

20

composed of the groups:

$$3[C - (H)_3(C)], \quad [C - (O)(C)_3], \quad 2[O - (O)(C)] \quad \text{and}$$

$$[C - (O)(C)_2(H)].$$
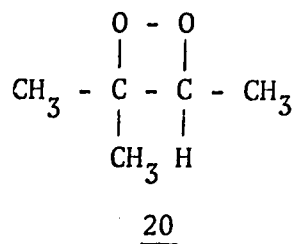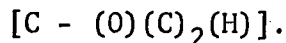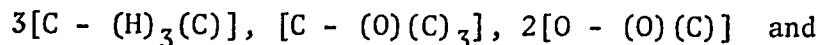
By using the contributions for these groups, making due allowance for ring-strain and applying a correction for the cis relation of two of the methyl groups, the thermodynamic parameters of 20 can be calculated. Since the ring-strain contribution for 1,2-dioxetanes is unknown an estimate of its value was made. The ring-strain contributions of cyclobutane and oxetane are 26.2 and 25.7 kcal mole^{-1}, respectively. The close similarity of these values suggest that the replacement of a methylene group by an oxygen atom makes little contribution to the

value of the ring strain correction. Consequently, the ring strain contribution of a 1,2-dioxetane ring is to a first approximation the same as that of oxetane. However, the 1,2-dioxetane ring incorporates the cis-rotation barrier of hydrogen peroxide, 7 kcal mole^{-1} (49), which must be added to the normal ring strain to give an estimated ring strain contribution of 32.7 kcal mole^{-1} for the 1,2-dioxetane ring.

The enthalpy change occurring during the decomposition of 20 to give ground state products, is given by equation [33].

[33] ΔH°_{298} (reaction) = $\Delta H^{\circ}_{f_{298}}$ (products) - $\Delta H^{\circ}_{f_{298}}$ (reactants)

For the reactant (20), the heat of formation is given by:

$$\Delta H^{\circ}_{f_{298}} = 3(-10.08) - 6.60 + 2(-4.5) - 7.00$$
$$+ 32.7 \text{ (ring correction)} + 1.0 \text{ (cis correction)}$$
$$= -19.14 \text{ kcal mole}^{-1}.$$

The cis-correction, 1.0 kcal mole^{-1}, has been added as an estimate of the strain introduced into 20 by the presence of two cis-related methyl groups (53). For the products, acetone and acetaldehyde, the combined heat of formation is -51.7 - 39.7 = -91.4 kcal mole^{-1} (53). The enthalpy change in the reaction is therefore ca. -72 kcal mole^{1}. Subtracting this value from the activation energy for the decomposition of 20, 22.9 kcal mole^{-1}, shows that ca. 95 kcal mole^{-1} is available to the products. The amount of energy is sufficient to give one n,π* excited singlet carbonyl compound but not a π,π* state or two excited molecules. The n,π* state of acetone, for example, is 83-87 kcal mole^{-1}

above the ground state (54), while the π,π^* state is at least 146

kcal mole^{-1} above the ground state (55). Clearly, neither the

suprafacial-suprafacial, nor the antarafacial-antarafacial modes of

decomposition can be operating during the decomposition of 20 because

they would lead to double excitation. The possibility that two triplet

state molecules are formed during the decomposition can also be

discounted because the n,π^* triplet state of acetone, for example,

lies at 79-82 kcal mole^{-1} above the ground state (54).

A possible mode of decomposition of 20 which gives only one

excited carbonyl fragment is one in which the potential energy surface

for suprafacial-suprafacial or antarafacial-antarafacial decomposition

crosses with another surface from which decomposition occurs to give

only one excited fragment. Such a mode of decomposition (Figure 11)

Reaction Coordinate
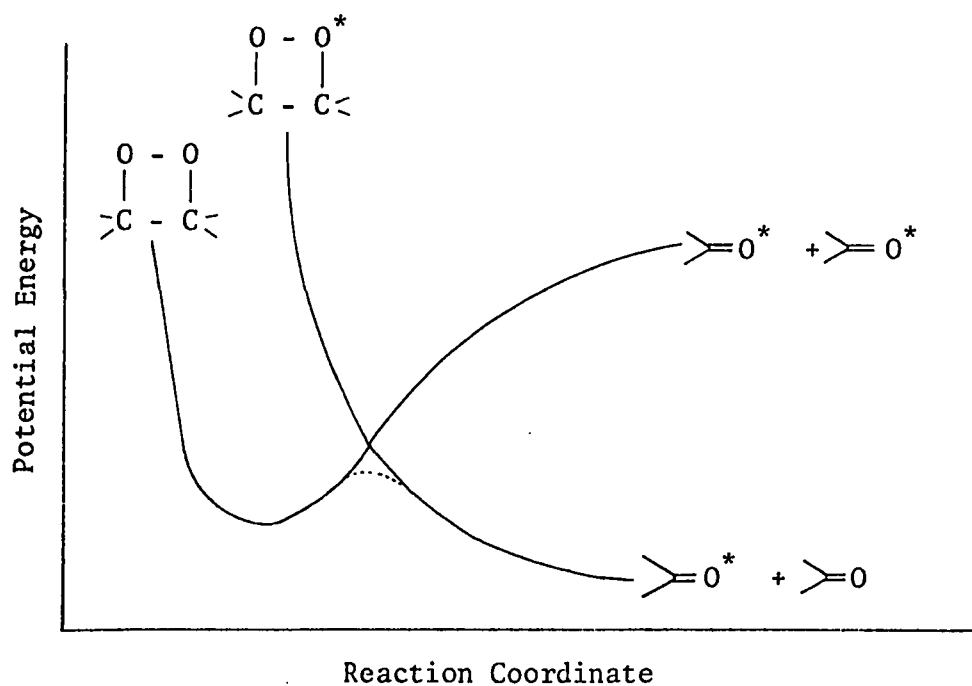
Figure 11. Crossing of states during the thermal decomposition
of 3,3,4-trimethyl-1,2-dioxetane (20).

would allow a lower energy pathway to be followed. A similar suggestion has been made to explain why the low-energy excited singlet state of butadiene is converted to ground state cyclobutene without having to pass through the high-energy excited singlet state of cyclobutene (56). (Also see footnote on page 94.)

One other possibility exists which might account for the formation of only one excited carbonyl fragment from the decomposition of 20, and that is, that the n-orbitals on the oxygen atoms of 20 have some, as yet unknown, unfluence on the course of the decomposition.

Thermochemical calculations (53) can also be applied to estimate the enthalpy change during the decomposition of cyclobutane. Using the data of Benson (53) the enthalpy change in the reaction at 0° is given by:

$$\Delta H^{\circ}_{298} = 2 \times \Delta H^{\circ}_{f_{298}} \text{ (ethylene)} - \Delta H^{\circ}_{f_{298}} \text{ (cyclobutane)}$$

$$= 2 \times 12.5 - 6.3$$

$$= 18.7 \text{ kcal mole}^{-1}.$$

However, the decomposition only proceeds rapidly at 730°K, so that it is necessary to estimate ΔH°_{730} for the reaction.

The molar heat capacity, C_p, of cyclobutane at 298°K is 17.3 gibbs mole^{-1}, and that for ethylene 10.3 gibbs mole^{-1}. Thus, the change in heat capacity for the reaction at 298°K is $2 \times 10.3 - 17.3 = +3.3$ gibbs mole^{-1}. Heat capacity data for cyclobutane is not available at higher temperatures so the value at 730°K was estimated using group additivity data and making linear interpolations between the known values to obtain the group C_p values at 730°K (53):

$$C^\circ_{p_{730}} \text{ (cyclobutane)} = 4\ C_p[C\text{-}(C)_2(H)_2] + \text{Ring correction}$$

$$= 4[10.47] - 2.15$$

$$= 39.73 \text{ gibbs mole}^{-1}.$$

For ethylene, C_p data at high temperatures was available from which $C^\circ_{p_{730}}$ was found by interpolation to be 18.8 gibbs mole^{-1}. From these figures, $\Delta C^\circ_{p_{730}}$ for the decomposition of cyclobutane was estimated to be 2 x 18.8 - 39.73 = -2.13 gibbs mole^{-1}. Thus, the average value of ΔC°_p over the range 298-730°K was $\frac{1}{2}(3.3-2.13)$ = 0.59 gibbs mole^{-1}. The heat of reaction at 730°K was then estimated using equation [34] (53).

$$[34] \qquad \Delta H^\circ_{730} = \Delta H^\circ_{298} + \Delta C^\circ_{p_{T_m}} (T_2 - T_1)$$

$$= 18.7 + 0.59 \times 432/1000$$

$$= + 18.96 \text{ kcal mole}^{-1}.$$

Subtracting this figure from the activation energy, 62.5 kcal mole^{-1}, for the reaction (53), the net energy available to the products is only ca. 44 kcal mole^{-1}. This energy is insufficient to give an excited ethylene molecule. The π,π^* state of ethylene is 133 kcal mole^{-1} above the ground state (57).

In similar fashion the enthalpy change during the decomposition of oxetane at 430° is estimated to be +19.75 kcal mole^{-1}. Subtracting this value from the activation energy for decomposition at 430°, 60.0 kcal mole^{-1} (53), leaves ca. 40 kcal mole^{-1} available to the products. Again, this energy is insufficient to give either excited ethylene, 133 kcal mole^{-1} (57), or excited formaldehyde, 81 kcal mole^{-1} (58).

The results of these latter calculations are not unexpected since the products of the decomposition of cis- and trans-1,2-dimethylcyclobutane are best explained in terms of a two-step reaction involving a biradical intermediate, rather than a concerted one-step reaction (59). For example the recovery of some trans-1,2-dimethylcyclobutane from the partial decomposition of cis-1,2-dimethylcyclobutane, indicates that biradical formation can be followed by rotation and recyclization, eq. [35] (59).
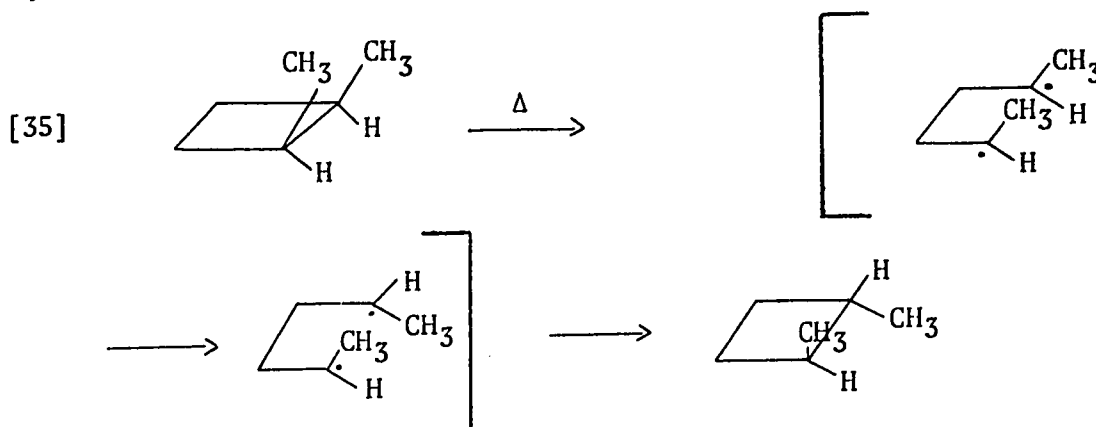
The Role of Four-membered Cyclic Peroxides in Chemiluminescence and Bioluminescence:

The luminescence observed during the decomposition of 20 certainly confirms the suggestion (39) that four-membered cyclic peroxides are responsible for many instances of chemiluminescence and bioluminescence. The luminescence wavelength maximum is at 430-440 mμ when 20 is decomposed in benzene at 60° (Figure 7). The shift in position of the maximum with time is probably due to a concentration effect (54,60).

The excited singlet state of acetone lies between 83 and 87 kcal mole^{-1} above the ground state (54) and that of acetaldehyde must have a similar energy. The shortest wavelength emission in the luminescence

spectrum of decomposing 20, at ca. 340 mμ, corresponds to an energy

loss of 84 kcal mole^{-1} which is very close to the energy of excited

singlet acetone (54).

Comparison of the position of the maxima with the positions of

the fluorescence wavelength maxima of acetone (54,60) and acetaldehyde

(61) also make it apparent that one of these compounds is produced in

the excited singlet state upon decomposition of 20. Two types of

fluorescence (60) are observed from acetone: monomer emission with

wavelength maximum at 345 mμ (60), which is observed at low

concentrations and excimer emission with wavelength maximum reported

at 405 (60) and 415 mμ (54) at higher concentrations (0.02 and 0.2 M,

respectively) in hexane at 25°. The fluorescence wavelength maximum

of acetaldehyde is at about 420 mμ (61), and it is likely that the

position of its maximum is also concentration dependent. Short

wavelength emission from a monomeric excited carbonyl compound (60) is

not expected from the decomposition of 20 at any initial concentration,

because the excited carbonyl compound is necessarily formed together

with another carbonyl compound in the same solvent cage.

The position of the 0 → 0 band of neither acetone (54) nor

acetaldehyde (61) is known so that it is not yet possible to decide

which of these compounds is produced in the excited state during the

decomposition of 20.

Further evidence that the luminescence observed in the

decomposition of 20 is due to the formation of an excited singlet

carbonyl compound comes from the results of energy transfer experiments.

Energy transfer to biacetyl from the excited singlet state of acetone

becomes very inefficient below 0.01 M biacetyl concentration (62). Under these conditions intersystem crossing to the excited triplet state of acetone can occur and energy transfer to biacetyl is again possible even at much lower concentrations of biacetyl (62). Thus strong emission was observed in the decomposition of 20 in the presence of 0.2 M biacetyl (which could be due to energy transfer from either excited singlet or triplet carbonyl compound) and also in the presence of 0.002 M biacetyl which could only be due to emission from an excited triplet state. The colors observed when benzene solutions of 20 containing anthracene, pyrene or napthacene were decomposed, were due to fluorescence from excited singlet states of these molecules. The intensities of luminescence were greater when these materials were present because they fluoresce much more efficiently, ϕ ca. 0.5 (63), than does acetone ϕ = 0.01 (54).

The chemiluminescence observed in the decomposition of 20 is unique in the sense that 20 serves as a model for the four-membered cyclic peroxides which have been implicated in many chemiluminescent and bioluminescent processes. Radziszewski (64), Trautz (65) and others (66) have listed a very large number of reactions where chemiluminescence can be observed. Other reviews (67, 68, 69, 70) have attempted to provide explanations for many cases of chemiluminescence and bioluminescence.

In 1964 McCapra and Richardson (71) suggested that the chemiluminescence of 10,10'-dimethyl-9,9'-biacridinium nitrate (22) and similar compounds (71) was due to the thermal decomposition of 1,2-dioxetanes, eq. [36].

[36]

22

23
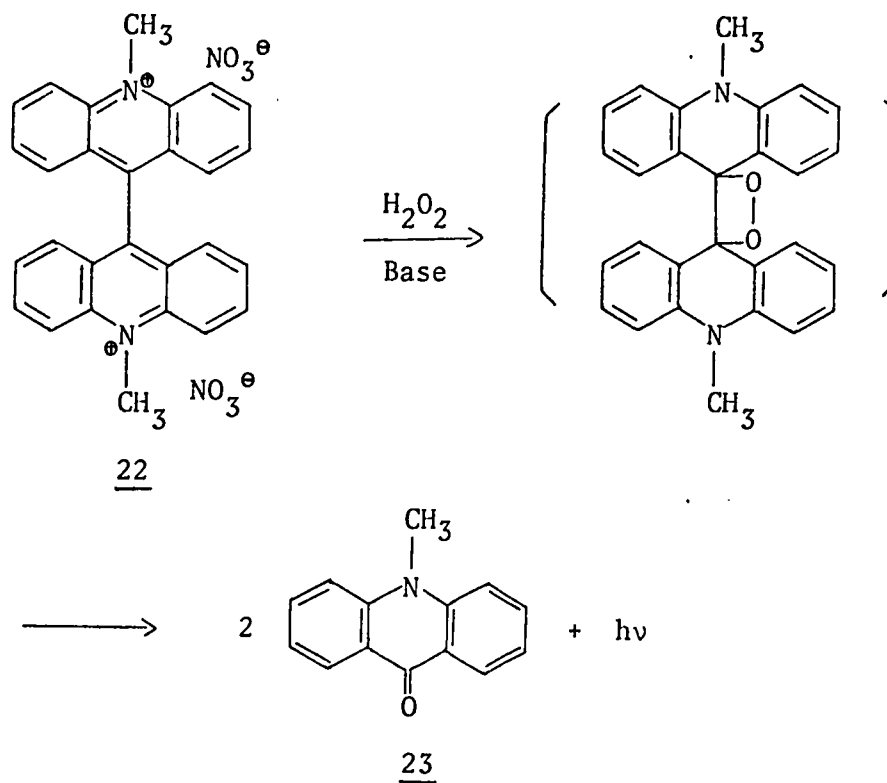
It was suggested that the chemiluminescence was due to emission from an excited singlet state of N-methylacridone (23).

Independently, White and Harding (72) and McCapra with Richardson (71) proposed that the decomposition of four-membered cyclic peroxides was also the source of light in bioluminescence. Bioluminescence involves the interaction of an enzyme (Luciferase) with another substance (Luciferin) (73). The luciferin of the firefly has been isolated from at least six different species (74) and its structure is now known (75) to be that of compound 24.

$R_1 = R_2 = H$.

24
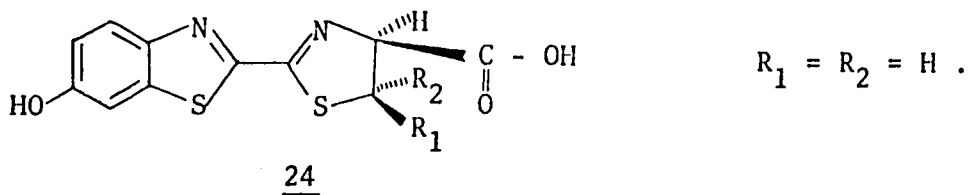
In nature the luciferin, 24, occurs as the mixed carboxylic-phosphoric anhydride in combination with adenosine monophosphate (76). A model system (77) in which $R_1 = R_2 = CH_3$, gave a bright red luminescence on treatment with base and oxygen. White and co-workers (76,78) have also synthesized systems where $R_1 = H$, $R_2 = H$; $R_1 = CH_3$, $R_2 = H$; and where $R_1 = H$, $R_2 = CH_3$. They report that these compounds give a bright green luminescence which more closely resembles the natural bioluminescence. They suggest (76) that green luminescence is due to emission from an excited dianion (25).

R = H   or   R = CH_3
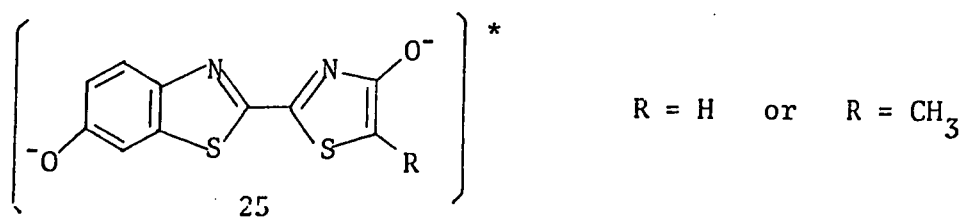
The mechanism of bioluminescence in this system is thought to result from the thermal decomposition of the four-membered cyclic peroxide, 26, eq. [37] (76).

[37]

R = Adenosine .
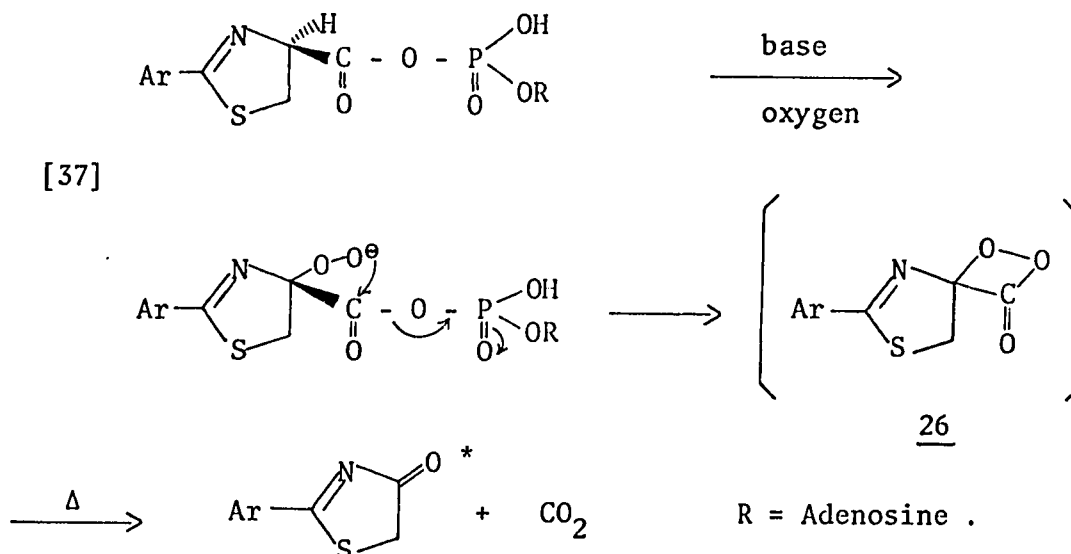
The luciferin of the crustacean, Cypridina, has been characterized (79). This compound, 27, has two possible sites for generating cyclic peroxides.
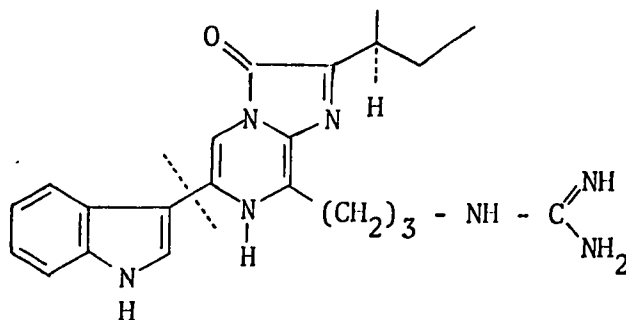
27

Two model systems have been studied which in effect isolate the two hetrocyclic sections (broken line) of the Cypridina luciferin. McCapra and Chang (80) studied the luminescence of indolenyl peroxides, eq. [38].

[38]
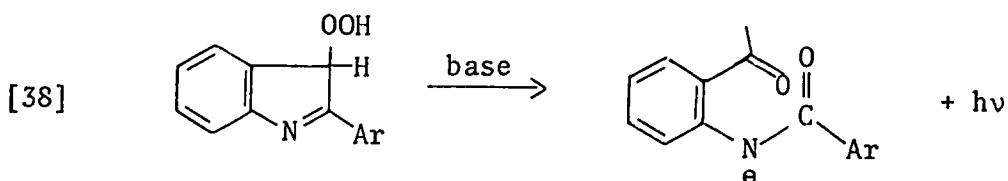
McCapra with Wrigglesworth (81) also studied a model for the remaining portion of 27, eq. [39].

[39]
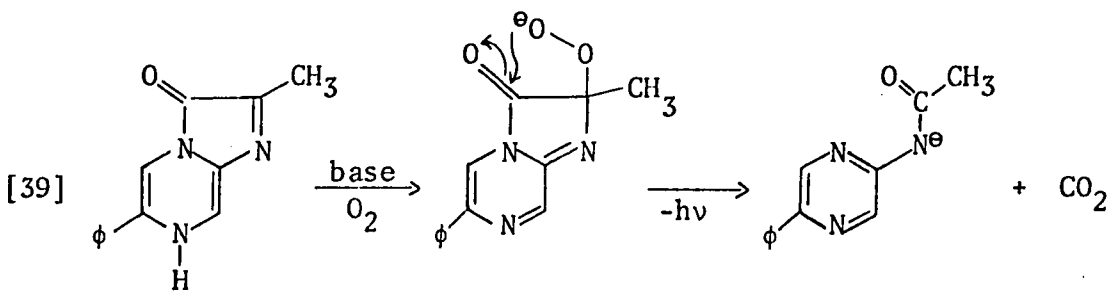
It is apparent from these examples, that although bioluminescence is a wide-spread phenomenon and that a wide variety of structures exists for the luciferins, the common link is always the formation of a four-membered cyclic peroxide.

The luciferin of a snail, (28), Latia neritoides, has been isolated (82) and seemed at first sight to be quite unrelated to the above systems.
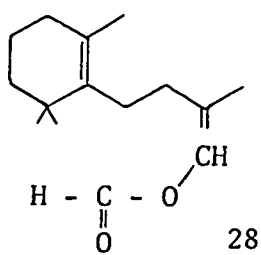
McCapra and Wrigglesworth (83) have suggested that this enol formate, 28, combines with the luciferase to form a Schiff's base, which is then attacked by oxygen. The feasibility of this suggestion was demonstrated (83) using, as a model, a Schiff's base of iso-butyraldehyde (29), eq. [40].
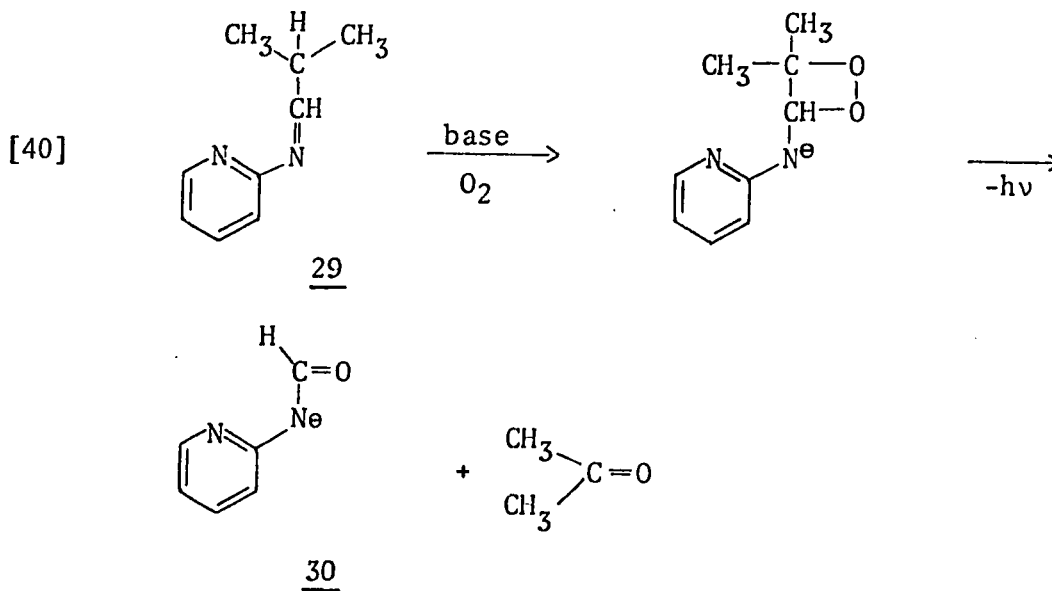
The emission spectrum of luminescence matched the fluorescence spectrum of the formamide ion (30). The authors (83) further suggested that the aldehyde-dependence of bacterial luminescence (84) is due to autooxidation of Schiff's bases formed between the added aldehyde and some constituent within the bacteria.

The 1,2-dioxetanes from many of these biological and model systems seem to have a very transitory existence at ambient temperatures. The excited singlet carbonyl compounds formed in these cases are conjugated and their excited singlet states should possess much lower energies than those of acetone, 83-87 kcal mole^{-1} (54), and acetaldehyde. Also, the 1,2-dioxetanes in these systems would be substituted by groups more bulky than the methyl groups of 20 and should therefore be more strained. In support of these suggestions McCapra and Hann (85) claim to have evidence for an aromatic 1,2-dioxetane with a life time of only 30 seconds, eq. [41].

[41]
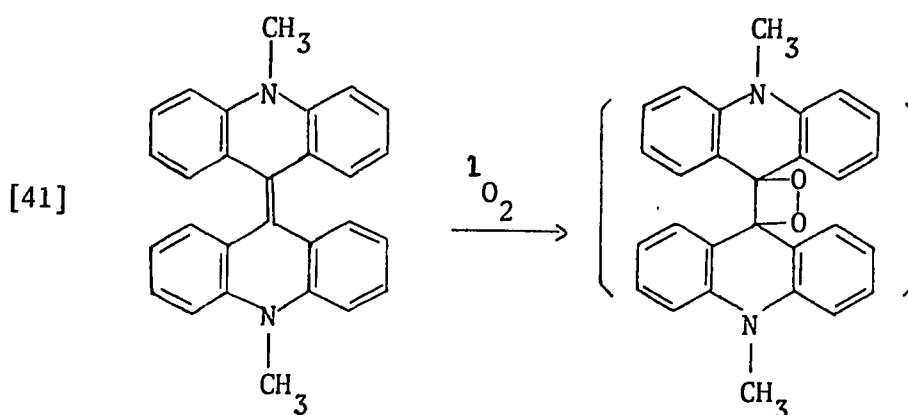
The reaction mixture continued to luminesce for 30 seconds after the source of singlet oxygen, $^1O_2$, was removed. The product of reaction

was N-methylacridone.

Another important chemiluminescent reaction is the oxalyl chloride-hydrogen peroxide system. The chemiluminescence of this reaction was first noted by Chandross (86). He suggested that the observed luminescence was due to emission from oxalyl chloride itself because the luminescence wavelength maximum was of insufficient energy to be due to excited carbon dioxide which was one of the products. Rauhut and co-workers (87) have discovered that a volatile product can be swept out of the reaction mixture which is not in itself chemiluminescent, but which gives a strong luminescence when passed into a solution of 9,10-diphenyl anthracene. They have considered the possibility that 1,2-dioxetanedione (31) is formed in the reaction, eq. [42].
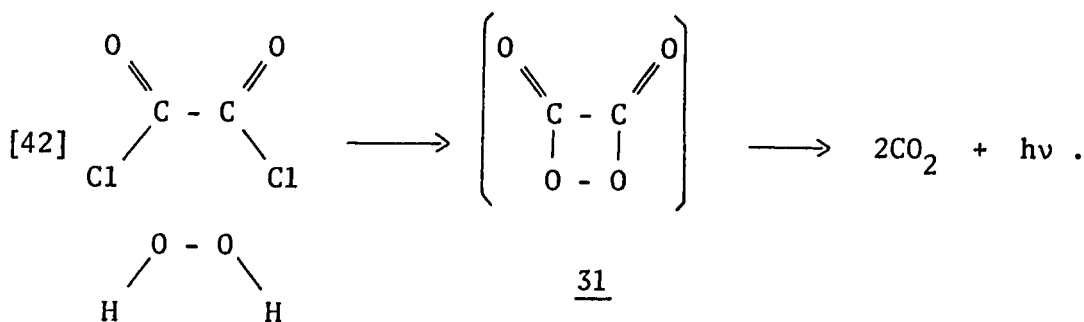
This suggestion was supported by the fact that the infrared spectrum of the volatile products was identical with that of carbon dioxide (87), which is derived from 31.

Some estimate can be made of the enthalpy change accompanying the decomposition of 1,2-dioxetanedione, (31), using group additivity increments (53). The ring strain contribution to the heat of formation

of 31 was assumed to be similar to that used for 3,3,4-trimethyl-1,2-dioxetane (20). The heat of formation of 31 is given by:

$$\Delta H^o_{f_{298}} = 2\Delta H^o_{f_{298}} [O - (O)(C)] + 2\Delta H^o_{f_{298}} [CO - (O)(C)]$$

$$+ \text{ Ring correction}$$

$$= 2x(-4.5) + 2x(-33.4) + 32.7$$

$$= -43.1 \text{ kcal mole}^{-1}$$

$\Delta H^o_{f_{298}}$ for carbon dioxide $= -94.05$

$\therefore \Delta H^o_{f_{298}}$ (reaction) $= -145 \text{ kcal mole}^{-1}$

If the assumption is now made that the activation energy for decomposition of 1,2-dioxetanedione is ca. 25 kcal mole^{-1}, as in the case of 3,3,4-trimethyl-1,2-dioxetane (20), then the enthalpy available to the products is ca. 170 kcal mole^{-1}. Since the energy of the first excited singlet state of carbon dioxide is at least 110 kcal mole^{-1} (88) above the ground state, it would appear that the luminescence in the oxalyl chloride-hydrogen peroxide system occurs via energy transfer from excited singlet carbon dioxide.

Early References to 1,2-dioxetanes.

The real existence of 1,2-dioxetanes has been a subject for controversy for many years. Many of the early claims have been disproven and others are easily dismissed in the light of the known properties of 3,3,4-trimethyl-1,2-dioxetane (20). For example, the peroxides isolated by Busch and Dietz (89) from the autooxidation of phenylhydrazones are now known to be hydroperoxides (90), eq. [43],

and not cyclic peroxides.

[43] R_1\ $C = N - NH - \phi$ $\xrightarrow{O_2}$ R_1\ $C - N = N - \phi$ (with $O-OH$ group)
        R_2/ R_2/
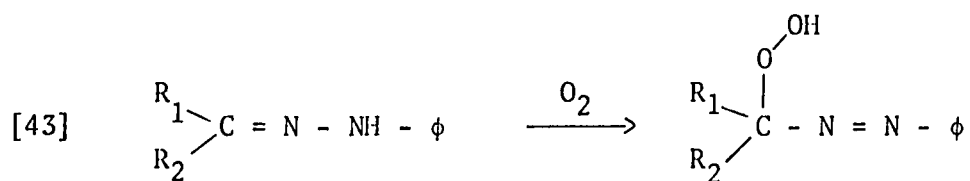
Similarly, the peroxides obtained by Kohler from the autooxidation of
enols (91) are known to be α-hydroperoxy ketones (92), eq. [44].

[44] ϕ\ $CH - CH = C$ ... $\xrightarrow{O_2}$ ϕ\ $CH - CH - C$ ...
       ϕ/ ϕ/
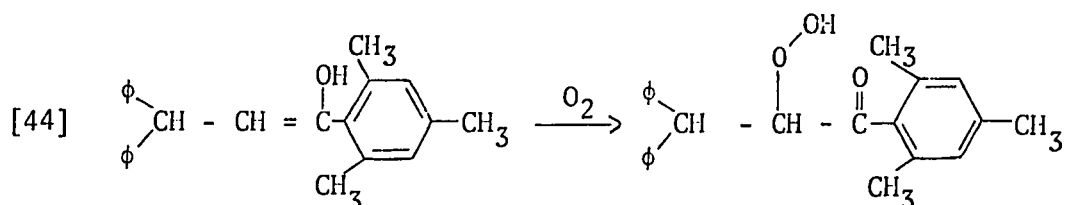
Interestingly, Kohler reported (91) that these peroxides decomposed
with a flash on heating, and that the products of decomposition were
carbonyl compounds. This work has been extended by Fuson (93) and
Doering (94, 95). Doering observed (94) that the oxygenation of
enolates at 70° gave rise to cleavage products, eq. [45], while at
room temperature

[45]   (benzene ring)$-CH_2-C(=O)-$(benzene ring) $\xrightarrow[O_2,\ 70°]{base}$ (benzene ring)$-C(=O)-OH$
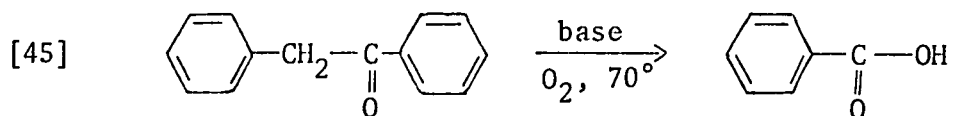
benzilic acid derivatives were obtained, eq. [46].

[46]
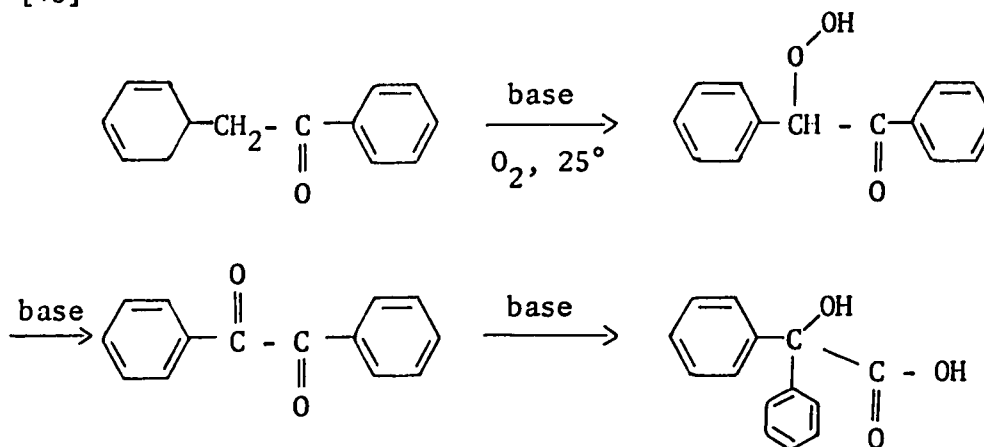
The formation of cleavage products (94), eq. [39], was rationalized by assuming that the powerfully nucleophilic, hydroperoxy anion (96) attacked the adjacent carbonyl centre to give a 1,2-dioxetane intermediate, eq. [47].

[47]
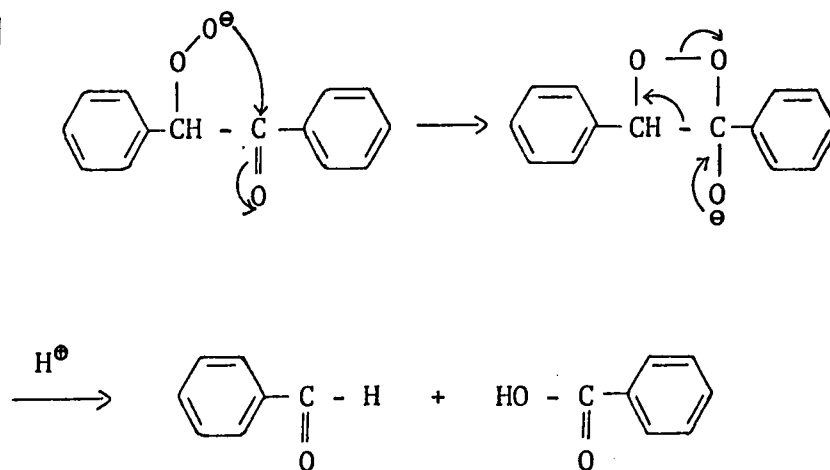
In 1956 Griffin and Lutz (97) pointed to the generality that all molecules containing the functionality $\diagup C = \overset{\displaystyle |}{C} - X - H$, where $X = O$, or N, are very susceptable to autooxidation. For example,

1-benzyl-2,3-diphenyl-2,3-dehydropiperazine (32) underwent rapid

autooxidation. The peroxide obtained underwent a rapid cleavage

reaction under mild conditions, eq. [48].

[48]
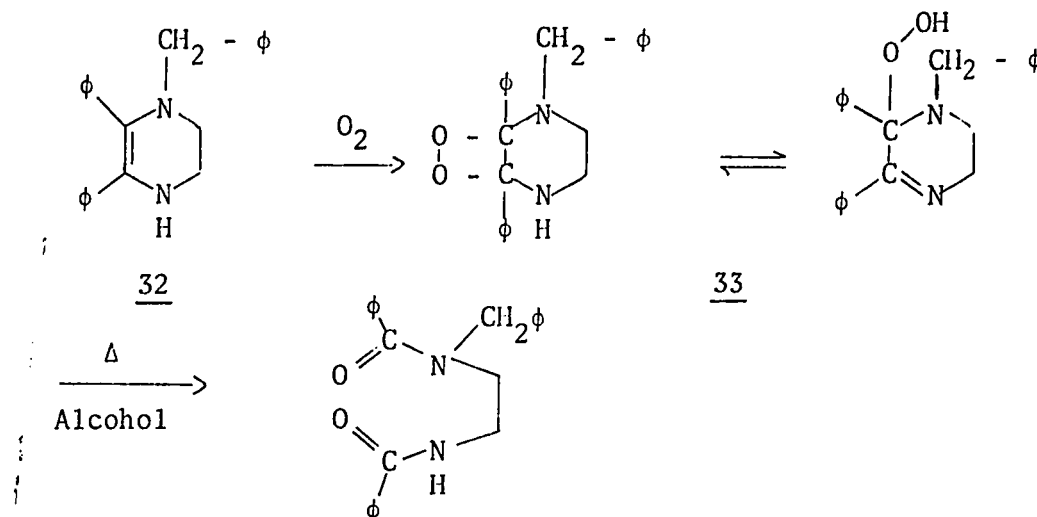
Infrared spectral analysis of the autooxidation product, 33, showed

no adsorption which could be attributed to a hydroperoxy group.

Furthermore the U.V. spectrum showed no absorption which could be

assigned to a Schiff's base. Consequently, the authors (97) suggested

that the autooxidation product was probably a four-membered cyclic

peroxide.

These observations were hotly disputed by Witkop and co-workers

(98,99) who suggested that the hydroperoxides, actually formed in

such reactions, undergo rapid acid catalyzed cleavage before the spectra

could be recorded. By rapid scanning of the infrared spectrum Witkop

and Patrick (98) were able to record the hydroperoxy group absorption

for the autooxidation product, 35, of tetrahydrocarbazole (34) eq. [49].

[49]

O_2, Pt.

$H^{\oplus}$

34   35
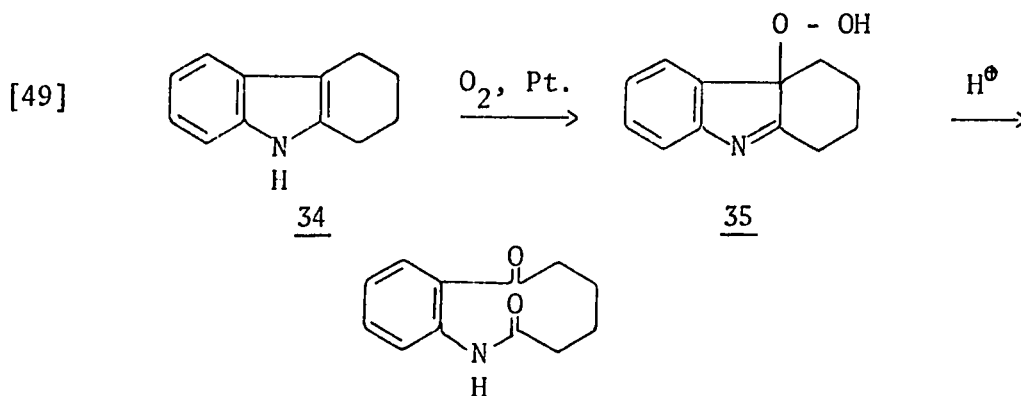
It is interesting to note that at 124° the hydroperoxide, 35, melts (100) and decomposes with a vivid blue flash. McCapra and co-workers have confirmed (101) that decomposition of the hydroperoxide, 35, is indeed a chemiluminescent process, but the acid catalyzed decomposition did not give rise to light emission.

In 1925 Staudinger (102) claimed to have isolated a number of cyclic peroxides from the autooxidation of ketens. Explosive reaction products were isolated at -20° which decomposed violently to a ketone and carbon dioxide at higher temperatures, eq. [50].

[50] $\displaystyle \begin{matrix} R \\ \ \\ R \end{matrix}\!\!>\!\! C = C = O \ + \ O_2 \ \xrightarrow[-20°]{} \ \left[\begin{matrix} R \\ \ \\ R \end{matrix}\!\!>\!\! \begin{matrix} C - C \!\!\nearrow^{\!O} \\ |\quad| \\ O - O \end{matrix}\right] \ \xrightarrow{+18°} \ \begin{matrix} R \\ \ \\ R \end{matrix}\!\!>\!\! C = O \ + \ CO_2$
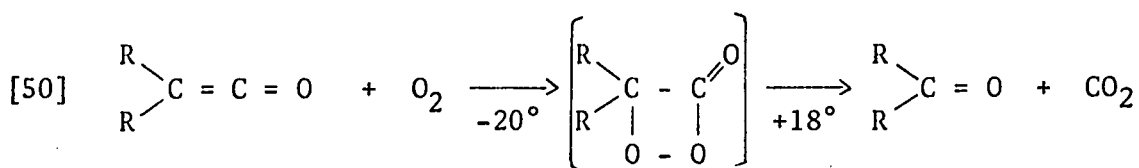
This work has recently come under reinvestigation. Jenny and co-workers (103) used isotopically enriched oxygen and discovered that the atoms of the oxygen molecule became equally divided among the products of keten autooxidation. The autooxidation of vinylidene chloride produced similar behavior (104), eq. [51].

$$[51] \quad CH_2 = C{\Large<}^{Cl}_{Cl} \quad \xrightarrow[24\ h]{O_2} \quad \left[\begin{array}{c} O - O \\ | \quad | \\ CH_2-C{\Large<}^{Cl}_{Cl} \end{array}\right]^{Cl}$$

0.5% (insoluble)
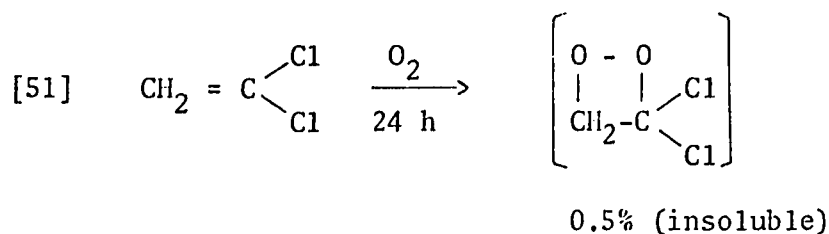
The white solid exploded on scratching, gave formaldehyde as its 2,4-dinitrophenyl hydrazone, and gave diphenyl urea on treatment with aniline. As Staudinger pointed out (102) with these compounds it is difficult to differentiate between a monomeric and polymeric peroxide. Some of these materials were insoluble in the parent solution and are probably polymeric in nature (105).

In 1935 Lucas, Prater and Morris (106) proposed that over a wide range of temperature, the autooxidation of 2-butenes proceeded via the initial formation of 3,4-dimethyl-1,2-dioxetane, eq. [52].

$$[52] \quad CH_3 - CH = CH - CH_3 \quad \xrightarrow[375-490°]{O_2} \quad \left[\begin{array}{c} H \quad\ H \\ | \quad\ | \\ CH_3 - C - C - CH_3 \\ | \quad\ | \\ O - O \end{array}\right]$$
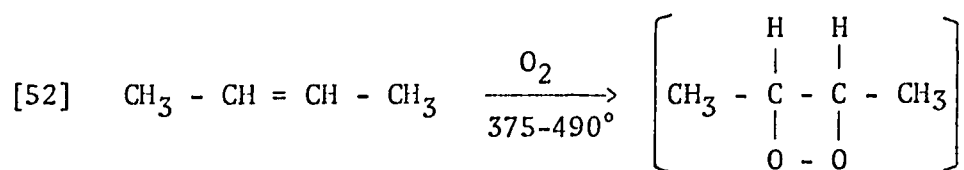
Consistent with the intermediacy of a 1,2-dioxetane, acetaldehyde was the major product at all temperatures. Other products were thought to be due to the pyrolysis of acetaldehyde (106).

Gunstone and Hilditch (107) also proposed the intermediacy of 1,2-dioxetanes in the autooxidation of olefins to account for the formation of allylic hydroperoxides. However, such behavior has not been observed in the case of 3,3,4-trimethyl-1,2-dioxetane (20).

Swern and co-workers reported (108) the formation of a cyclic peroxide during the autooxidation of methyl oleate. They claimed

that polarographic analysis of the autooxidation products detected only hydroperoxides while iodimetry detected all peroxides. The hydroperoxide estimation was lower than the iodometric content of peroxide in all the autooxidations. The authors attributed the difference to the formation of four-membered cyclic peroxides. Reduction with sodium bisulphite, potassium iodide in acetic acid, or by hydrogenation gave vicinal glycols which were estimated by titration. The formation of glycols was taken as evidence for the formation of a 1,2-dioxetane. The temperature of autooxidation, 35-120°, seems too high for a 1,2-dioxetane to survive. The results are more in keeping with the formation of cross-linked polyperoxides. Similar results to these were found by Paquot (109) who suggested that several modes of olefin autooxidation exist.

Recently, four-membered cyclic peroxides have been invoked to explain the cleavage products obtained in some sensitized photooxygenation reactions. Foote and co-workers have made the most detailed studies (110,111). Photooxygenation of the enamine 36 (110) gave rise to the formation of an unstable product which underwent cleavage at room temperature, eq. [53].

[53]
$$\begin{array}{c}CH_3 \\ \\ CH_3\end{array}C = C\begin{array}{c}H \\ \\ N\end{array}\begin{array}{c}CH_3 \\ \\ CH_3\end{array} \xrightarrow[\text{Sens.}]{O_2,\ h\nu} \begin{array}{c}CH_3 \\ \\ CH_3\end{array}C = O \quad + \quad O = C\begin{array}{c}H \\ \\ N - CH_3 \\ | \\ CH_3\end{array}$$

36
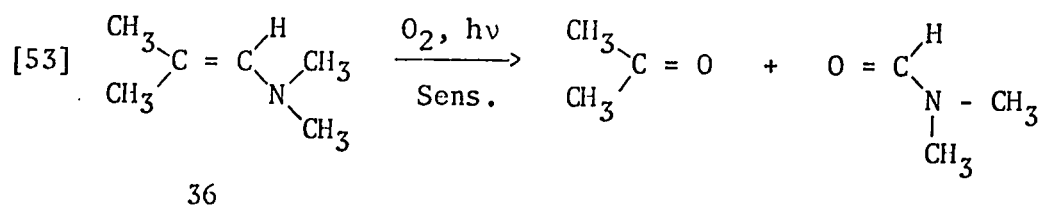
The low temperature n.m.r. spectrum of the unstable intermediate showed absorption at τ 5.0-5.5 (1H), τ 7.4-7.6 (6H) and τ 8.3-8.9 (6H).

When the photooxygenation of β-piperidinostyrene (37) was carried out

at -60° followed by reduction with sodium borohydride reduction,

2-N-piperidino-1-phenylethanol (38) was obtained in 72% yield (110),

eq. [54].

[54]
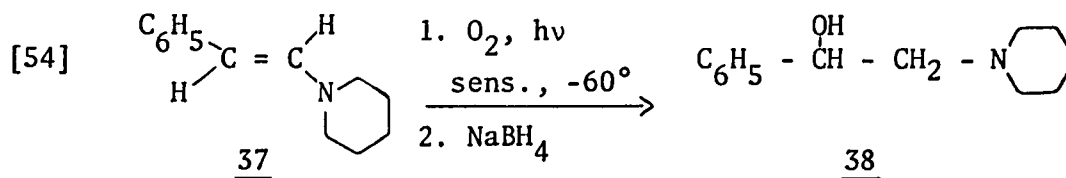
Foote has remained noncommital in the interpretation of these results.

Huber (112) has reported a similar cleavage reaction during the

photooxygenation of a steroidal enamine. Similar cleavage has been

reported in the case of certain olefins. Schenck (113) obtained

exclusively cleavage in the reaction of eq. [55].

[55]
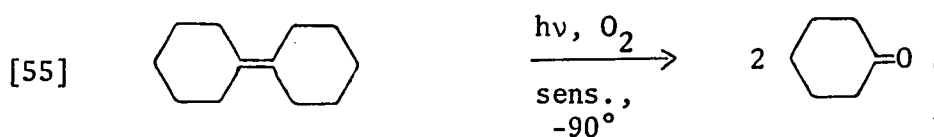
The photooxygenation of indene (114) in methylene chloride also gave

rise to cleavage products in quantitative yield, but in methanol some

methoxy hydroperoxides were also obtained, eq. [56].

[56]
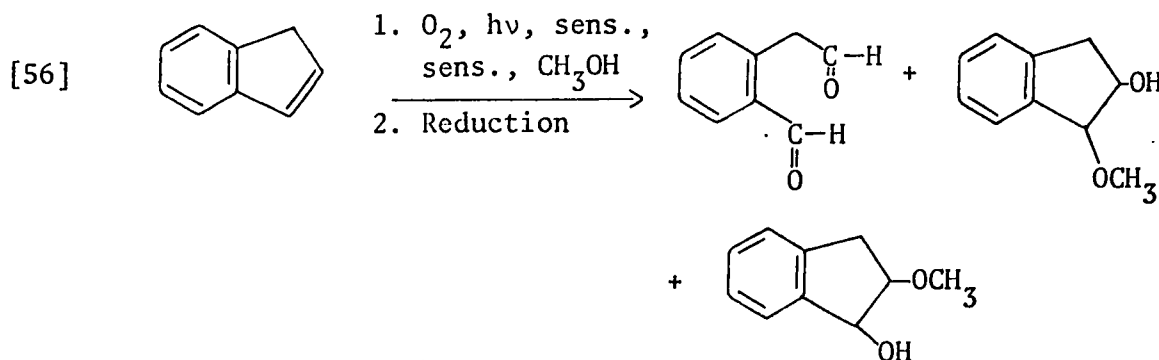
The formation of methoxy hydroperoxides was thought to be due to solvolysis of the 1,2-dioxetane (39), eq. [57].

[57]
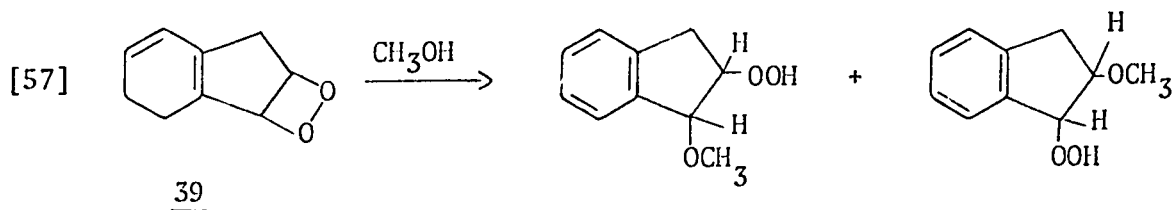
This type of behavior has not been observed in the case of 20, and is more in keeping with the formation of the perepoxide (40), eq. [58].

[58]
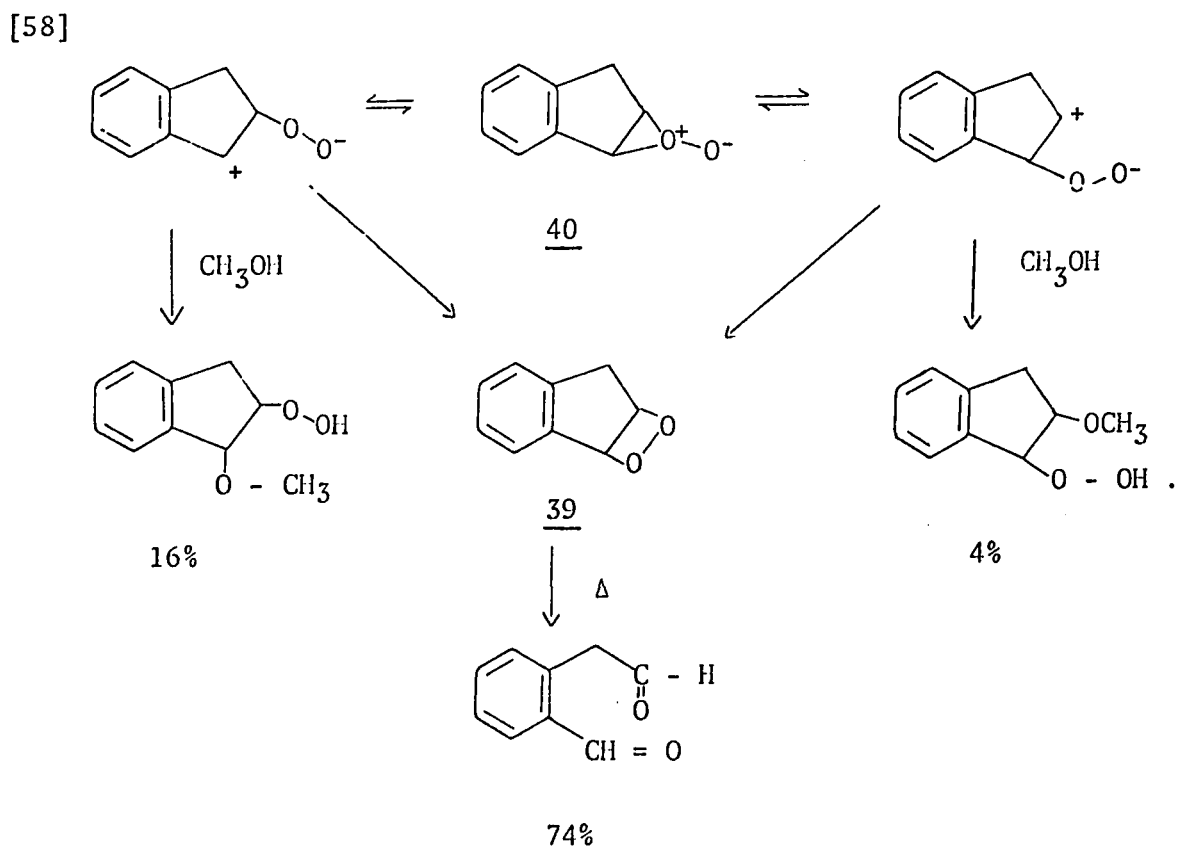
The Future of Chemiluminescence:

As mentioned previously, the excited carbonyl compound formed in the thermal decomposition of 3,3,4-trimethyl-1,2-dioxetane should be capable of performing the well-known photochemical reactions of acetone or acetaldehyde. One of these processes, energy transfer to acceptor molecules, has been demonstrated in this work. Very recently White and co-workers have shown (115) that other photochemical processes work equally well. For example, trans-stilbene can be isomerized to cis-stilbene, eq. [59],

[59]
$$\phi\!\!>\!\!C = C\!\!<\!\!H/\phi \quad \xrightarrow[\text{80°, 7 minutes}]{\underline{20},\ \text{benzene}} \quad \phi\!\!>\!\!C = C\!\!<\!\!\phi/H \quad (20\%)$$
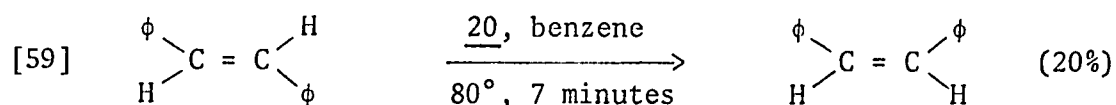
and 4,4-diphenylcyclohexadienone (41) has been converted to 6,6-diphenyl-[3,1,0]-bicyclohexene-1-one (42), eq. [60] (115).

[60]

$$\xrightarrow[\text{80°, 10 minutes}]{\underline{20},\ \text{benzene}}$$

(25%)

41   42
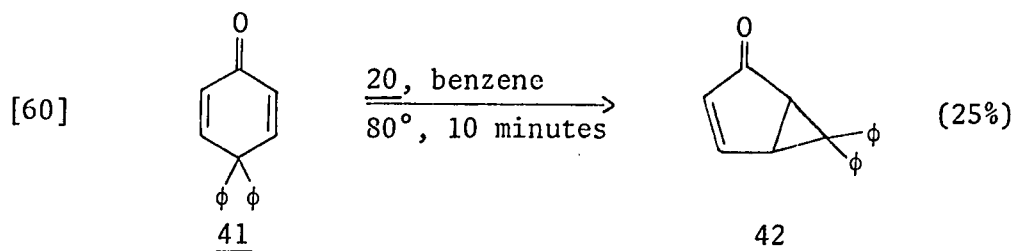
This new technique of "Photochemistry without Light" (115), not only gives quantum yields of products comparable with those of conventional organic photochemistry, but also offers several advantages. For example, given a supply of 20 or similar substance, photochemical reaction times are very much shorter. Also, with the new technique there is less probability of the photochemical products being themselves photolyzed, a factor which would greatly simplify work-up of reaction

mixtures and hence, interpretation of the results. Furthermore, the apparatus required for these reactions can be found in any organic chemistry laboratory, thus bringing organic photochemistry within the reach of small colleges, undergraduates and industrialists.

NOTE ADDED IN PROOF. (See page 73.)

D. R. Kearns and A. U. Khan, Photochem. and Photobiol., 10, 193 (1969), have also concluded that the decomposition of 1,2-dioxetanes would have to proceed via crossing of states for the reaction to be concerted.

EXPERIMENTAL

Preparations of 3,3,4-trimethyl-1,2-dioxetane (20) were always carried out on a small scale because of the potential explosive character of this material. As a result of this precaution no explosions were observed during the course of this work, but occasionally solutions of 20 were accidentally contaminated with indigenous laboratory dust and immediately evolved sufficient heat to boil the solvent away.

Rates of Reaction of 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) with Base at 0°:

A solution of 11 in methanol was prepared by dissolving 4.575 g of 91.7% pure 11 in methanol and adjusting the volume to 500 ml with methanol. By iodometric titration the prepared solution was found to be 0.05 M in 11. Portions of this solution (50.0 ml) were diluted with 7.5 ml of water and cooled with stirring in a stirred ice-water bath. When the temperature of the stirred solution had reached 0°, base was added consisting of 2.5 ml of 1.0 M, 2.0 M, or 3.0 M aqueous sodium hydroxide. The sodium hydroxide solutions were prepared by weighing A.R. sodium hydroxide which was stated to be at least 97% pure. At suitable time intervals, 10 ml samples were withdrawn by pipette and quenched by adding them to a mixture consisting of 20 ml water, 10 ml ether and 2 ml acetic acid contained in a separating funnel. The aqueous layer was separated and the organic layer washed

once with 5 ml water. The combined aqueous extracts were titrated with 0.020 M aqueous silver nitrate solution using as indicator 10 drops of aqueous 0.1% Eosin as the sodium salt. Aliquots taken during the early stages of the reaction gave only colloidal suspensions of silver bromide but nevertheless, there was no difficulty in observing the colour change of orange to violet. Each experiment was carried out in duplicate. Agreement between duplicate experiments was so good that the results were combined to produce one set of data. In trial experiments the weight of the reaction mixtures were measured as was the weight of one 10 ml sample of each mixture. The actual volumes of the cold mixtures were also measured by pouring the mixtures into a measuring cylinder. A knowledge of these quantities permitted a calculation of the infinity titer to be expected, and also permitted calculation of the actual concentrations of reactants at 0°. For example, in the reaction where 2.0 M sodium hydroxide was used, the total weight of the mixture was 49.4 g while the weight of a 10.0 ml sample was 8.55 g. Thus, each sample contained 0.173 of the total mixture from which the infinity titer, using 0.02 M silver nitrate, was estimated to be 21.6 ml. In practice the infinity titer for this run was found to be 22.50 ml. To allow for this discrepancy the concentration of the original solution of 11 was redefined in terms of bromine content as being 0.052 M. From the total volume of the reaction mixture (57.7 ml), and the weight of 11 present in the solution, the molarity of 11 was initially estimated to be 0.0449 M and the base concentration to be 0.0866 M. In a similar manner concentrations were calculated for the other runs using 1.0 M and 3.0 M

sodium hydroxide. The rate constants obtained are given in Tables I, II and III. An example of one of the second order plots is shown in Figure 1.

In the reaction where 1.0 M sodium hydroxide was used, iodometric titration of the total peroxide content was also performed. Again, 10 ml samples were withdrawn and quenched with 20 ml of 3:2 acetic acid-chloroform mixture. The mixtures were then estimated for total peroxide (30) using 0.05 M sodium thiosulfate. The total peroxide content fell more slowly than bromide ion was liberated and is shown in Figure 2.

Isolation of 3,3,4-Trimethyl-1,2-dioxetane (20):

A stirred solution of 3-bromo-2-methyl-2-butyl hydroperoxide (11) (2.00 g, 91.3% pure, 0.01 mole) in 6 ml methanol was cooled to 0° by means of an ice-water bath. Then base, consisting of 0.44 g, 1.1 equivalents sodium hydroxide dissolved in 1 ml water and 3 ml methanol, was added over a period of 10 minutes. Stirring was then continued for a further 1 hour and forty minutes at 0°. At this time an ice-cold mixture of 10 ml water and 10 ml carbon tetrachloride was added. After a further two minutes stirring, the organic layer was separated and dried over molecular sieves (4A). The resulting yellow solution was then transferred to a semi-micro distillation apparatus lacking a condenser and fitted with an air bleed. Without applying heat, the solution was evaporated into the receiving bulb of the apparatus which was cooled to -78° by immersion in a Dry Ice-acetone bath. The pressure was kept at ca. 15-20 mm to begin with, but was reduced gradually to ca. 0.5 mm until the evaporation rate had become negligible. The

condensate obtained was thawed and again evaporated in the same manner
as before except that only the final 20-30% of the volatile material
was collected. The resulting solution contained 20 in a yield of ca.
7-12%. The yield of 20 was increased to 17% when the scale of reaction
was doubled. The n.m.r. and infrared spectra have been described in
the results section.

Since the above preparative method was wasteful, an attempt was
made to separate 20 from unreacted 11 by column chromatography on
neutral alumina. However, when a carbon tetrachloride solution of 20
was added to the column, the column became very hot and the solvent
was observed to boil.

Hydrogenation of 3,3,4-Trimethyl-1,2-dioxetane (20):

A solution of ca. 0.1 g (0.001 mole) 20 in carbon tetrachloride
prepared as described above, was hydrogenated over palladium-on-charcoal
at one atmosphere pressure. Hydrogen uptake was very slow. After 70
hours, when 115 ml (S.T.P.) of hydrogen had been absorbed, the solution
was filtered and the solvent removed. Only a minute trace of residue
remained. N.m.r. analysis (CCl$_4$), of the residue, gave a spectrum
quite unlike that of the expected 2-methyl-2,3-butanediol (14). Some
of the peaks in this spectrum matched those of 3-bromo-2-methyl-2-
butanol (15), but the remaining peaks could not be identified.

Catalytic Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20):

A solution of ca. 0.1 g (0.001 mole) of 20 in 3 ml carbon
tetrachloride was allowed to stand over palladium-on-charcoal for 12
hours at 0°. At the end of this period the yellow color had been

destroyed. The n.m.r. spectrum of the colorless solution showed absorption due to acetone and acetaldehyde only. To gain some idea of the rate of catalyzed decomposition the experiment was repeated.

A mixture of 0.5 ml of 0.104 M 20 in carbon tetrachloride and 2 mg of palladium-on-charcoal was shaken violently in a sealed n.m.r. tube. Initially the n.m.r. spectrum had shown no trace of acetone absorption, but after 45 minutes shaking at 29°, decomposition had occurred to the extent of 13.5%. The yield of decomposition products, acetone and acetaldehyde, was estimated from the ratio of peak-areas of products and unreacted 20 in the n.m.r. spectrum. The rate of catalyzed decomposition was estimated, assuming first order kinetics, to be ca. 5.4×10^{-5} sec^{-1} at 29°. The rate of thermal decomposition at 29° was found, by extrapolation of rate data at higher temperatures, to be ca. 1.03×10^{-5} sec^{-1}.

Reduction of 3,3,4-Trimethyl-1,2-dioxetane (20) with Sodium Sulfite:

To a stirred solution of sodium sulfite (0.126 g, 1×10^{-3} mole) in 3 ml of water, was added 3 ml of 0.33 M 20 in carbon tetrachloride at 0°. The solution became progressively alkaline so 10% hydrochloric acid was added at intervals to maintain the pH at 7-9. When all the peroxide had been consumed, as shown by adding one drop of the organic layer to an acidified potassium iodide solution, the mixture was separated. The dried organic layer contained 2,3-epoxy-2-methylbutane (13) as shown by comparison of the n.m.r. and infrared spectra of the solution with those of an authentic sample of 13. The aqueous layer was acidified with 10% hydrochloric acid and then treated with barium chloride solution. A white precipitate of barium sulfate formed which

was collected by filtration. The yield of dried barium sulfate was
0.1618 g, (70%).

Reduction of 3,3,4-Trimethyl-1,2-dioxetane (20) with Potassium
Iodide in Acetic Acid Solution:

A mixture of 5 ml of 0.104 M 20 in carbon tetrachloride, 5 ml of
glacial acetic acid and 1 ml of saturated aqueous potassium iodide was
allowed to react for 15 minutes in the dark at room temperature. Then
sufficient 0.2 M aqueous sodium thiosulfate was added to exactly react
with the liberated iodine. The resulting mixture was then treated
with solid anhydrous sodium carbonate until the evolution of carbon
dioxide ceased. The resulting slurry was shaken for one hour periods
with each of four 25 ml aliquots of ether. The ether extracts were
combined by decantation from the slurry and dried. The residue obtained
on removing the ether was taken up in 1 ml carbon tetrachloride
containing toluene (0.1117 g, 1.21×10^{-3} mole) as internal standard.
The n.m.r. spectrum of this mixture was identical with that of authentic
2-methyl-2,3-butanediol (14). The yield of 14; 50%, was estimated
from the relative areas of the toluene methyl group absorption and the
methyl group absorptions of 14.

Thermal Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20):

A solution of 20 in carbon tetrachloride, containing a small
quantity of benzene as internal standard, was sealed inside an n.m.r.
tube. The n.m.r. spectrum was recorded and then integrated once.
Initially the ratio of benzene absorption to methyl group absorption
was 1.00:5.18. The sealed tube was then heated for 12 hours by

immersing it in a water bath at 60°. After this period the n.m.r. spectrum was again recorded and integrated once. The spectrum now showed absorption due to acetone and acetaldehyde but no trace of 20 was to be seen. After heating, the ratio of benzene absorption to methyl group absorption was 1.00:4.84. From these ratios it can be seen that 93% of the initial integration of 20 had reappeared as acetone and acetaldehyde. The final n.m.r. spectrum obtained when 20 was decomposed in pure carbon tetrachloride, has been described in the results section. The n.m.r. tube, used in the latter experiment, was opened and the products analyzed by g.l.c. on a 5 ft. x 1/4 in. column of 10% Carbowax 1500 on Chromosorb W at 50°. Only two peaks due to products were observed, which had retention times identical with those of acetone and acetaldehyde.

Rates of Thermal Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20) in Carbon Tetrachloride Solution:

A solution of 20 in carbon tetrachloride, contained in a 10 ml volumetric flask was immersed in a thermostatted bath. At intervals, ca. 1 ml samples were withdrawn and quickly weighed in a stoppered flask. After weighing, the samples were analyzed for 20 by iodometric titration (30). The sodium thiosulfate used was 0.01 M and end points were detected using starch indicator. The titration volumes were corrected for constant weight of sample and for a small residual peroxide titer. An example of the data obtained is presented in Table IV. Good first order plots were obtained at 40.2°, 50.2°, 55.3° and 60.8° as shown in Figure 4. The first order rate constants, k_d, are

summarized in Table V. The temperatures were measured using Fischer thermometer No. 2C4311 which had been calibrated by the National Bureau of Standards.

The thermal decomposition of 20 was also studied by n.m.r. spectroscopy. A solution of 20 in carbon tetrachloride containing benzene as internal standard was allowed to decompose at 36° in the probe of the n.m.r. spectrometer. The decomposition was followed for eight hours by recording the n.m.r. spectrum and peak integrations at suitable times. The spectra obtained are shown in Figure 7. The rate of decomposition was estimated from the change of integration due to acetone and acetaldehyde methyl-group absorption, relative to the integration of the added benzene. The spectral region between benzene absorption and methyl-group absorption was swept at high speed. The time of measurement was recorded at the completion of integration. The result is presented in Table V.

Luminescence in the Thermal Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20):

A faint bluish luminescence was observed when a benzene solution of 20, contained in a test-tube, was heated above 70° in the dark. Crude emission spectra were obtained with some difficulty. For this determination 6 ml samples of 0.21 M 20 were added to a water-jacketed, 10 cm polarimeter tube fitted with quartz windows. Water, at 60°, was pumped continuously through the water jacket from a thermostatted water bath. The light from the decomposing 20 passed through a manually-operated Bausch and Lomb 500 mm monochromator, and thence to an RCA 1P28 photomultiplier tube which was fastened to the monochromator with

black tape. The output from the photomultiplier was fed to a recorder. The whole apparatus was contained in a darkened room. The emission was measured at 10 mμ intervals allowing 15 seconds for each reading. In this way the spectra were obtained as a series of steps. The emission at each wavelength was then corrected for photomultiplier response according to the manufacturer's specification. Spectra were obtained for 0.21 M, 0.021 M and 0.0021 M 20 however, the latter was very poor. The former spectra are shown in Figure 8 with smooth lines drawn between the points.

Luminescence was enhanced considerably when benzene solutions of 20 containing 0.1 M anthracene, 0.1 M pyrene or 0.1 M napthacene were heated above 70°. The observed colors, violet, turquoise and green, respectively, were matched by the fluorescence produced when benzene solutions of these added compounds were irradiated with ultraviolet light.

Intense green emission was also observed when a degassed solution of 20 in benzene containing biacetyl was heated above 70°. A solution 0.104 M in 20 and 0.2 M in biacetyl was prepared by mixing equal volumes of 0.208 M 20 in benzene and 0.4 M redistilled biacetyl in benzene. The solution was twice degassed by means of freezing and thawing under high vacuum. On heating the sample to 70° a brilliant glow was observed which cast shadows of the surrounding objects. The intensity of the emitted light was much greater than that from a similar sample lacking biacetyl. Repeating the experiment using 0.002 M biacetyl gave a similar result.

Rate of Decomposition of 3,3,4-Trimethyl-1,2-dioxetane (20) in the Presence of Biacetyl:

A solution of 0.22 M 20 in benzene containing 0.2 M biacetyl was decomposed by heating at 60.8°. As described previously, for decomposition of 20 in carbon tetrachloride solution, samples were removed at intervals for up to three half-lives and titrated for peroxide content. The rate of decomposition, k_d, was found to be 11.3 x 10^{-4} sec^{-1}. In the absence of biacetyl the rate of decomposition of 20 in benzene at 60.8° was 5.5 x 10^{-4} sec^{-1}.

CHAPTER III

THE BASE-PROMOTED REACTION OF 3,3,4-
TRIMETHYL-1,2-DIOXETANE

In Chapter I preliminary evidence was presented which showed that the reaction of 3-bromo-2-methyl-2-butyl hydroperoxide (11) with base did not lead to the formation of an allylic hydroperoxide. In Chapter II it was shown that the primary product of the above reaction was in fact 3,3,4-trimethyl-1,2-dioxetane (20). Since van de Sande (4) had suggested that 1,2-dioxetanes were the precursors of allylic hydroperoxides it became of interest to study the base-promoted reaction of 20.

RESULTS AND DISCUSSION

Because the isolation of 3,3,4-trimethyl-1,2-dioxetane (20) was
a tedious and wasteful process, it was decided to circumvent this
difficulty by generating 20 in situ. The reaction of the
bromohydroperoxide, 11, with excess base would provide an almost
quantitative yield of 20 and permit use of both aqueous and alcoholic
solutions. N.m.r. spectra had been obtained for both 11 and 20 so
the further reaction of 20 with excess base could be followed
conveniently by n.m.r. spectroscopy.

Reaction Between 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) and

Sodium Methoxide:

(a) Spectroscopic Study.

An ca. 1 M solution of 11 in methanol-d_4, contained in an n.m.r.
tube, was allowed to react with 1.7 equivalents of sodium methoxide-d_3
at 0°. The mixture was placed in the probe of an n.m.r. spectrometer
at 0°. Spectra were recorded at intervals and are shown in Figures
12a-e. The first spectrum (25 minutes reaction) showed the presence
of 11 and 3,3,4-trimethyl-1,2-dioxetane (20) in the ratio of ca. 1.8:1
(Figure 12a). The ratio was judged from the relative peak heights of
the quartets at τ 5.37 (11) and τ 4.63 (20). After 76 minutes reaction
the quartets at τ 5.37 and τ 4.63 were of equal height indicating that
the ratio of 11:20 was now 1:1 (Figure 12b). In addition to the eight
absorptions of the two major components, at high field, a small peak

Figures 12a-e. Nuclear magnetic resonance spectra recorded during

the reaction between 3-bromo-2-methyl-2-butyl

hydroperoxide (11) [ca. 1.0 M] and sodium methoxide-d_3

[ca. 1.7 M] in methanol-d_4 at 0°, a) 25 minutes reaction,

b) 76 minutes reaction, c) 121 minutes, d) 156 minutes,

e) 225 minutes.

Figure 12f. Nuclear magnetic resonance spectrum of the mixture

obtained after 20 hours reaction between 3-bromo-2-

methyl-2-butyl hydroperoxide (11) [ca. 1.0 M] and

sodium methoxide [ca. 1.7 M] in methanol at 0°.

Figure 12g. Nuclear magnetic resonance spectrum of 2-methyl-2,3-

butanediol (14) in methanol-d_4.
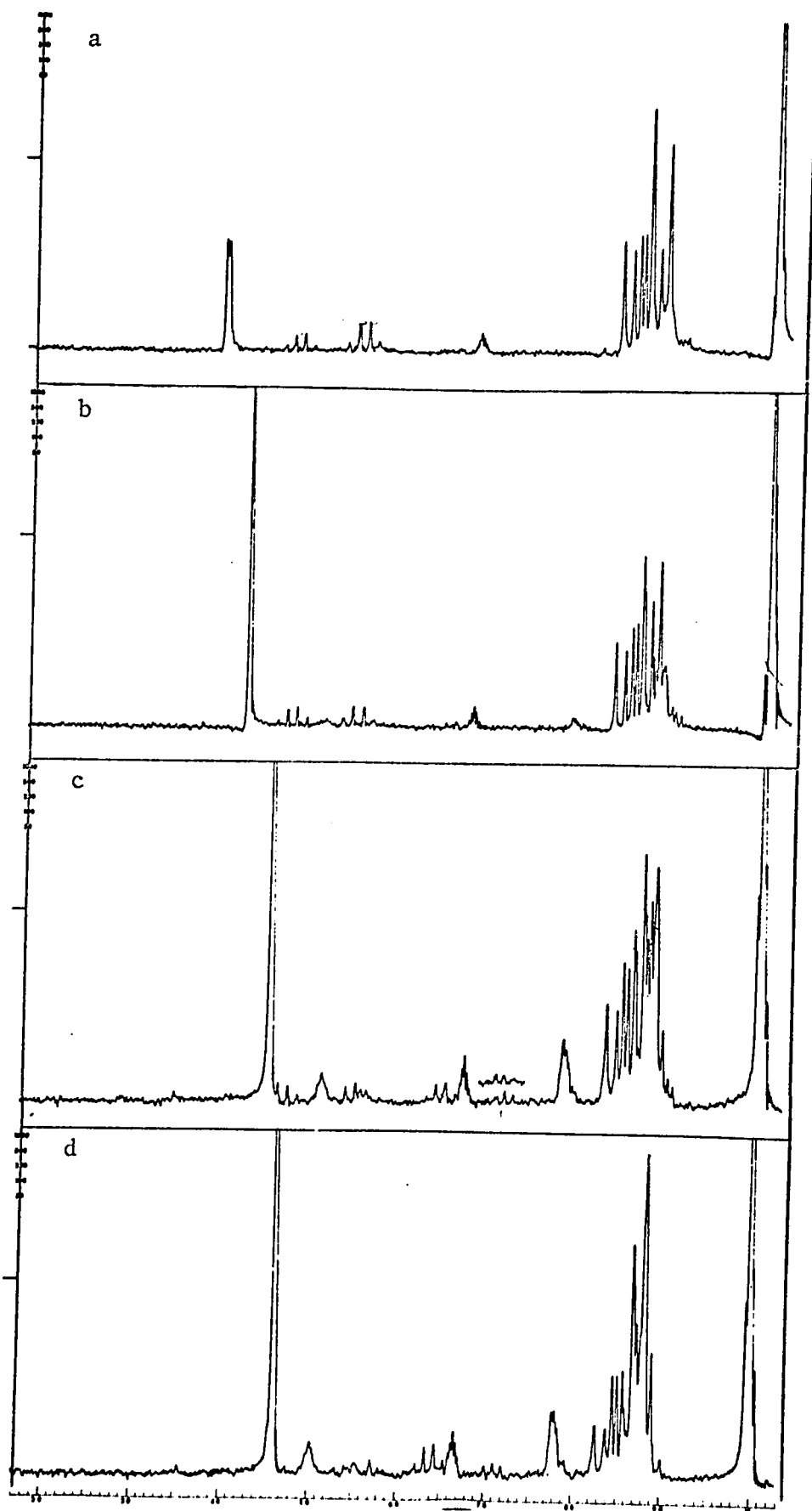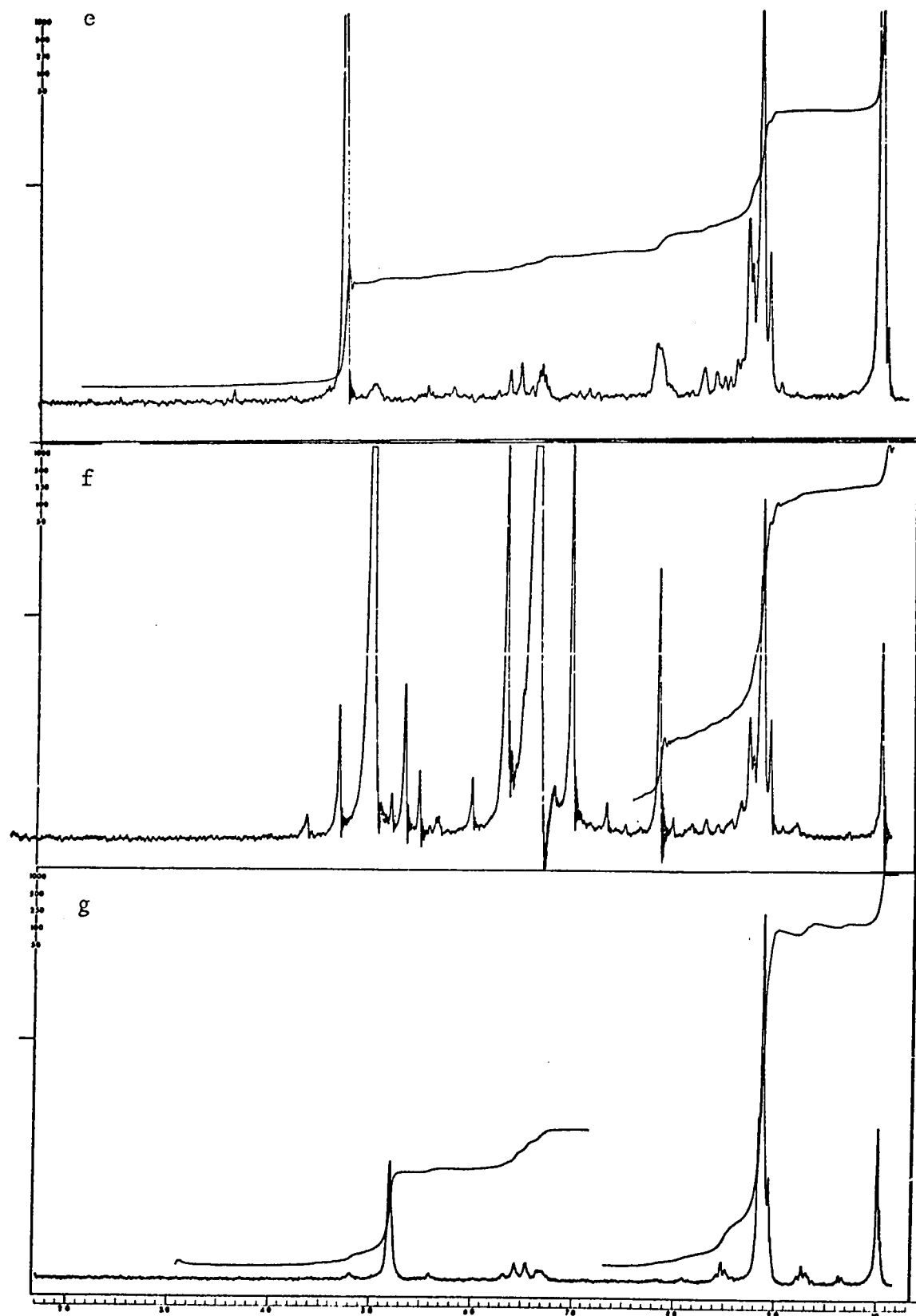
had appeared at τ 8.83, and also a small multiplet at τ 7.75 - τ 7.90. After a reaction time of 121 minutes the three quartets visible were of approximately equal size (Figure 12c). The new quartet at τ 6.39 seemed to be associated with the rapidly growing τ 8.83 peak, and another new peak at τ 8.92. There were also faint indications of a fourth quartet at τ 7.08.

After 156 minutes reaction the quartet at τ 4.63 had become obscured by the rapidly growing hydroxyl absorption while the quartet at τ 5.37 had essentially disappeared (Figure 12d). The quartet at τ 6.39 had increased in height relative to the methanol CD_2H impurity absorption. The quartet at 7.08 and the multiplet at τ 7.7 - 7.9 were unchanged. The region τ 8.2 - 9.0 still showed absorptions of 11 and 20, but the most prominent peak was now at τ 8.83.

After 225 minutes the spectrum showed the quartet at τ 6.40, J = 6.4 c.p.s., a multiplet at τ 7.7 - τ 8.0, and a multiplet at τ 8.53 - 9.0 with the maximum at τ 8.83 and other maxima at τ 8.71, τ 8.73 and τ 8.92 (Figure 12e). The peak at τ 8.83 also exhibited a shoulder on its low field side. The continuous increase in the size of the hydroxyl absorption during the reaction (Figures 12a-e) was due to exchange of deuterium with the protons of carbonyl compounds.

The reaction described above was repeated on a larger scale using methanol as solvent and sodium methoxide as base. After 20 hours, the n.m.r. spectrum of the reaction mixture was similar to the final spectrum of the above reaction. The 20 hour spectrum, Figure 12f, shows that the shoulder on the τ 8.83 peak (methanol-d_4) was now resolved and appeared at τ 8.81. This peak, and the peak at τ 8.92

formed a doublet centered at τ 8.86, J = 6.4 c.p.s. In addition, the
spectrum showed a sharp singlet at τ 7.81 where only a multiplet had
appeared in deuterated methanol. The position of this latter peak
corresponded exactly with that of acetone in methanol. The actual
yield of acetone under these conditions is not known with certainty
but is estimated to be ca. 30% from the n.m.r. spectrum of the
20-hour-old reaction mixture. When nitrogen was bubbled through a
similar, 4-hour-old reaction mixture for four hours, and the n.m.r.
spectrum examined, the peaks at τ 7.81, τ 8.71 and τ 8.73 had
disappeared leaving only the peaks at τ 8.86 (doublet, J = 6.4 c.p.s.)
and τ 8.83 (singlet). When evaporation was continued to small bulk,
the quartet at τ 6.40, seen in deuterated methanol (Figure 12e),
became visible. This n.m.r. spectrum was identical with that of
2-methyl-2,3-butanediol (14) in methanol-d$_4$. A spectrum of the glycol,
14, in methanol-d$_4$, is shown in Figure 12g.

Finally, the mixture was evaporated several times with carbon
tetrachloride. The sticky solid remaining was washed with carbon
tetrachloride and the n.m.r. spectrum of the resulting extract recorded.
The spectrum was identical with that of the glycol, 14, in carbon
tetrachloride solution. It was expected that the n.m.r. spectrum of
this final product would show methoxyl group absorption, eqs. [61] or
[62], but none was observed. It should be noted that the products of

[61]

$$
\begin{array}{ccc}
\overset{\displaystyle O - O}{\underset{\displaystyle\begin{array}{cc}|&|\\ H & CH_3\end{array}}{CH_3 - C - C - CH_3}} & \xrightarrow[CH_3OH]{CH_3O^{\ominus}} & \overset{\displaystyle HO \quad O - O - CH_3}{\underset{\displaystyle\begin{array}{cc}|&|\\ H & CH_3\end{array}}{CH_3 - C - C - CH_3}} \\
20 & & 44
\end{array}
$$

[62] $CH_3 - \overset{\overset{\textstyle O - O}{\textstyle |\qquad|}}{\underset{\underset{\textstyle CH_3 \;\; H}{\textstyle |\qquad|}}{C - C}} - CH_3$ $\xrightarrow[CH_3OH]{CH_3O^{\ominus}}$ $CH_3 - \overset{\overset{\textstyle HO - O}{\textstyle |\qquad|}}{\underset{\underset{\textstyle CH_3 \;\; OCH_3}{\textstyle |\qquad\quad|}}{C - C}} - H$

20
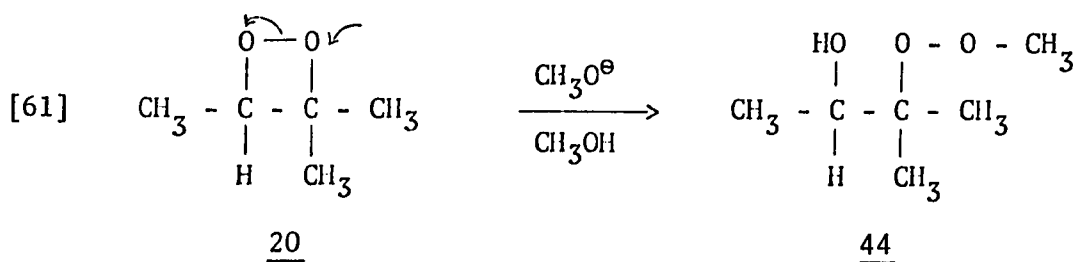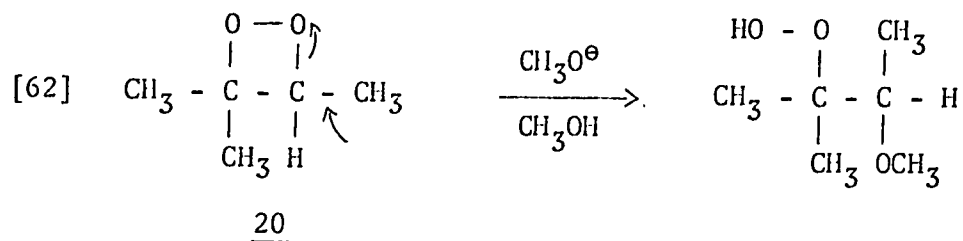
equations [61] and [62] would give n.m.r. spectra similar to those of the glycol **14**.

The remainder of the sticky solid, which had not dissolved in carbon tetrachloride, was dissolved in deuterium oxide and the n.m.r. spectrum recorded (external TMS). The spectrum again showed the absorption pattern of **14** and also a relatively small absorption at τ 8.0 (singlet) which did not exchange with the basic deuterium oxide. The lack of exchange meant that neither acetone nor acetaldehyde was responsible for the absorption.   It was thought that this absorption could be due to a trace of acetate ion derived from the hydrolysis of methyl acetate during work up, eq. [63].   Indeed, a solution of sodium acetate in deuterium oxide also absorbed at τ 8.0 in the n.m.r. spectrum.

[63]

$CH_3 - \overset{\overset{\textstyle O - O}{\textstyle |\qquad|}}{\underset{\underset{\textstyle H \;\; CH_3}{\textstyle |\qquad|}}{C - C}} - CH_3$ $\xrightarrow{}$ $\xrightarrow{CH_3OH}$ $CH_3 - \overset{\overset{\textstyle HO \;\; OH}{\textstyle |\qquad|}}{\underset{\underset{\textstyle H \;\; CH_3}{\textstyle |\qquad|}}{C - C}} - CH_3 + CH_3 - \overset{\overset{\textstyle O}{\textstyle \|}}{C} - OCH_3$

20   **14**
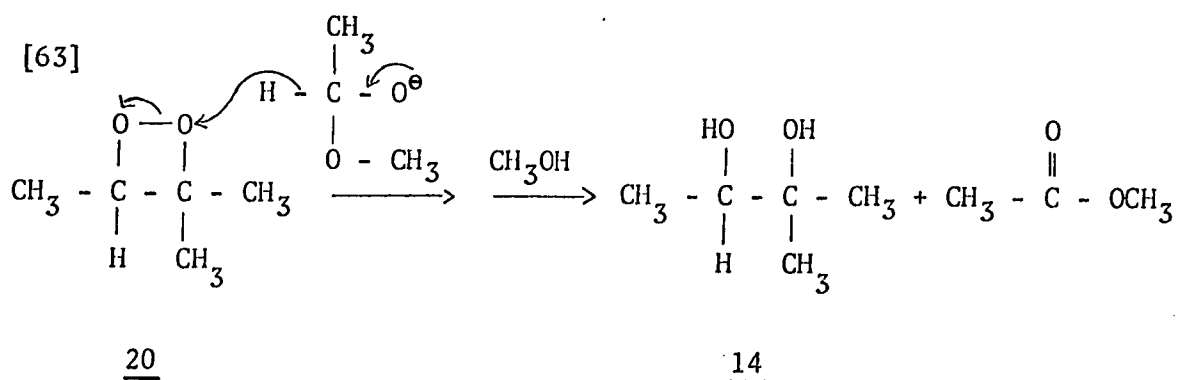
In this mechanistic scheme, eq. [63], the acetaldehyde hemiacetal, formed by the reaction of acetaldehyde and methanol, is thought of as

being a hydride transfer agent.

The volatile materials, which had been swept out of the reaction mixture, were collected in a cold trap and examined by g.l.c. for the presence of methyl acetate. However, the only materials present in the condensate were acetone, acetaldehyde and methanol.

In addition to the absorptions of acetone and the glycol, 14, the above n.m.r. spectra, (Figures 12a-f), contained extraneous peaks at τ 8.71 and 8.73. It was thought that acetaldehyde as the hemiacetal was in some way responsible for these unexplained absorptions because they disappeared when nitrogen was swept through the mixture. Acetaldehyde could arise, together with acetone, by thermal decomposition of 20. When the n.m.r. spectrum of acetaldehyde in methanol solution was examined, absorption was observed at τ 8.76 (doublet, J = 5.0 c.p.s.). Any other absorptions were obscured by solvent absorption. The n.m.r. spectrum of acetaldehyde in methanolic sodium methoxide was markedly temperature and time dependent. If the n.m.r. spectrum of an ice-cold sample of this mixture was recorded, absorption was observed at τ 5.02 (quartet, J = 5.0 c.p.s.) and τ 8.76 (doublet, J = 5.0 c.p.s.). As the initially cold sample warmed to 35° (probe temperature) the quartet at τ 5.02 rapidly disappeared (4 minutes) and the high field absorptions increased in complexity giving maxima at τ 8.73, 8.78, 8.82, 8.89 and 8.93. Any other absorptions were obscured by solvent peaks. Although these peaks did not exactly match those observed during the reactions of 11 with methanolic sodium methoxide, they undoubtedly make some contribution to the pattern.

(b) Rate of Loss of Total Peroxide.

In Chapter II, evidence was obtained for the existence of the 1,2-dioxetane, 20, by comparing the rate of loss of the total peroxide content with the rate of appearance of bromide ion during the reaction of bromohydroperoxide 11 with base. Consideration of all the ways by which 20 might react with base, revealed that the total peroxide should also be unchanged during reaction of 20 with base except for one possibility, eq. [64].

[64]

$$
\begin{array}{ccc}
\text{O - O} & & \text{HO} \quad \text{O} \\
\text{CH}_3 - \overset{|}{\underset{|}{\text{C}}} - \overset{|}{\underset{|}{\text{C}}} \cdots \text{H} \overset{\curvearrowleft}{\cdots} \text{B} \longrightarrow \longrightarrow & & \text{CH}_3 - \overset{|}{\underset{|}{\text{C}}} - \overset{\|}{\text{C}} - \text{CH}_3 \\
\text{CH}_3 \quad \text{CH}_3 & & \text{CH}_3 \\
20 & & 43
\end{array}
$$
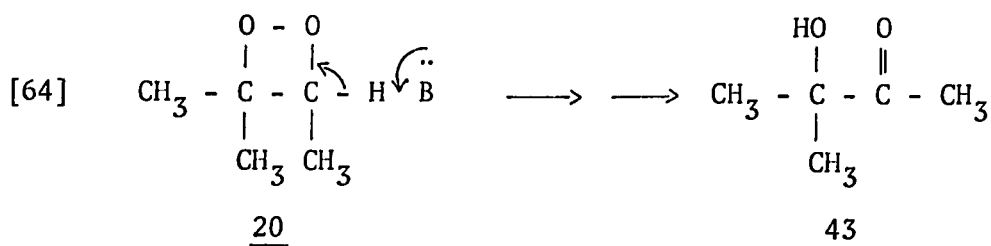
However, compound 43 was not present to any significant extent in the products of reaction of 11 with base, so that it was apparent that the reaction of the generated 20 with base must lead initially to another peroxidic product. This conclusion was tested by titrating the reaction mixture for total peroxide content during the time these changes were taking place.

The main bulk of the reaction mixture in methanol ('a' above) was titrated at intervals for total peroxide content. Under these conditions the peroxide content of the mixture fell steadily (Figure 13). By comparing the variation of peroxide content with the accompanying changes in the n.m.r. spectrum observed in 'a' above (Figures 12a-e), it is clear that the peroxide content falls as the final product is formed. It is also apparent that the large excess of base
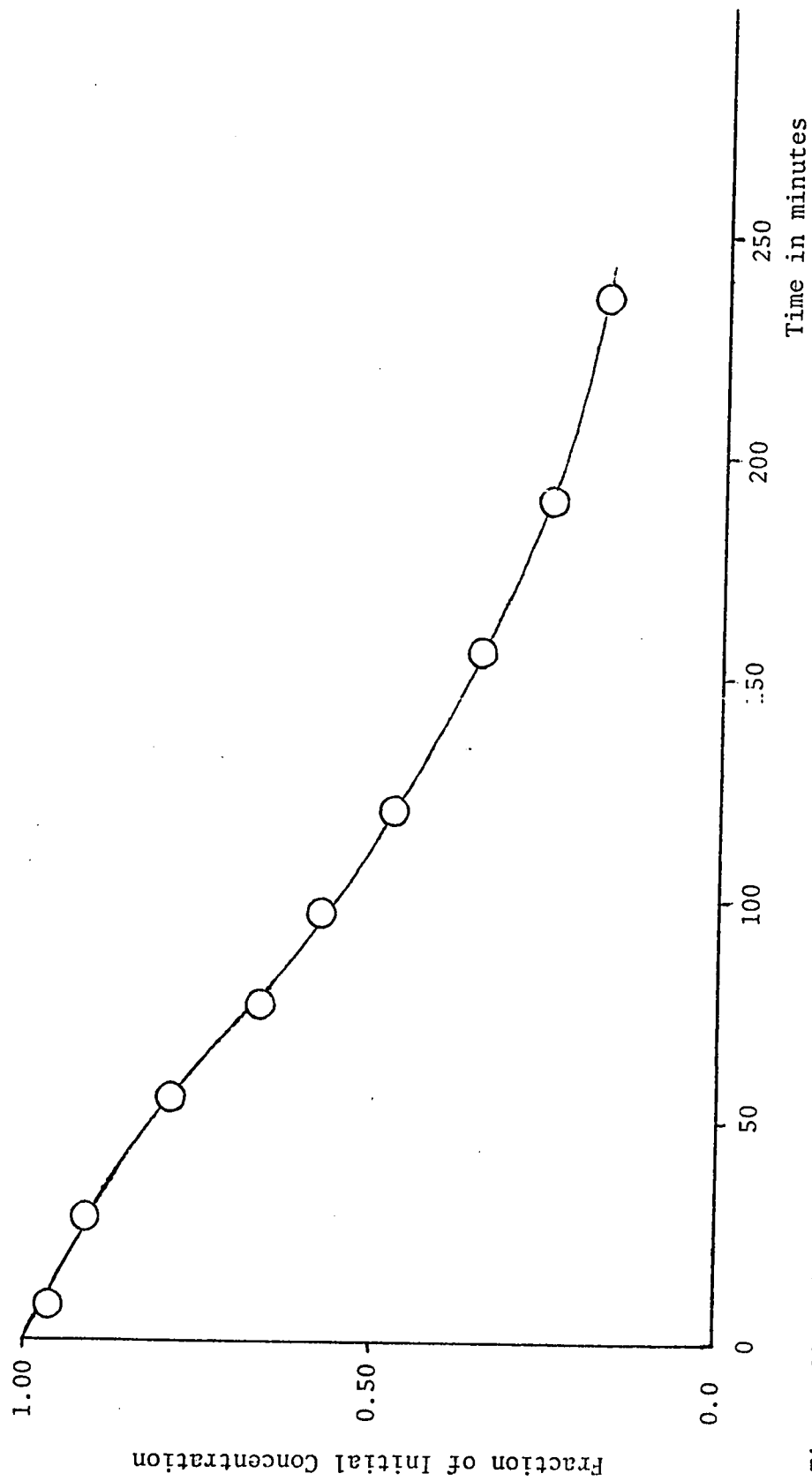
Figure 13. Change in total peroxide content during the reaction of 3-bromo-2-methyl-2-butyl hydroperoxide (11) [ca. 1.0 M] with methanolic sodium methoxide [ca. 1.7 M] at 0°.

(0.7 equivalents) in the present reaction results in a faster rate of loss of peroxide than was observed in Chapter II for a reaction where only 0.1 equivalents of excess base were used. The ultimate product, derived from the reaction of bromohydroperoxide 11 with base, was non-peroxidic and was either the glycol 14 or some closely related material. By analogy with the mechanism of reaction of 20 with sulfite ion and with iodide ion, it seemed that methoxide ion would also attack 20 in a similar manner, eq. [65], to give the mixed peroxide 44.

$$
[65] \quad
\begin{array}{c}
\text{O} - \text{O} \\
| \quad | \\
\text{CH}_3 - \text{C} - \text{C} - \text{CH}_3 \\
| \quad | \\
\text{H} \quad \text{CH}_3 \\
\underline{20}
\end{array}
\quad
\xrightarrow[\text{CH}_3\text{OH}]{\text{CH}_3\text{O}^{\ominus}}
\quad
\begin{array}{c}
\text{HO} \quad \text{O} - \text{O} - \text{CH}_3 \\
| \quad\quad | \\
\text{CH}_3 - \text{C} - \text{C} - \text{CH}_3 \\
| \quad\quad | \\
\text{H} \quad\quad \text{CH}_3 \\
\underline{44}
\end{array}
$$
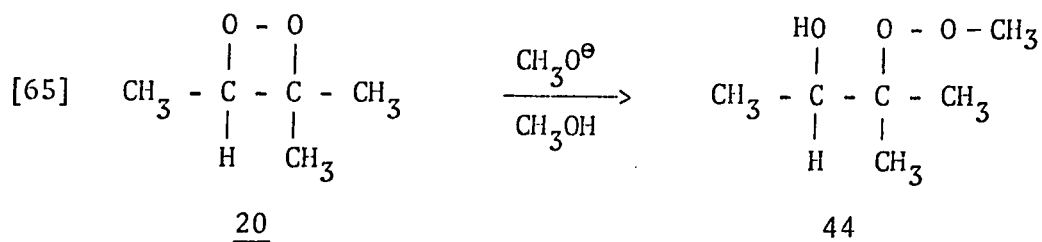
The mixed peroxide 44 would have a similar n.m.r. spectrum to that of the glycol, 14, and might be very sluggish in its reaction with iodide ion. Dimethyl peroxide is reported to be only slowly reduced by potassium iodide in acetic acid (116). In other words, the loss of total peroxide during the reaction of the bromohydroperoxide, 11, with base might have been only an apparent loss. However, as mentioned above, the final product of the reaction of 11 with base did not show any absorption in the n.m.r. spectrum which could be attributed to the methoxy group, and could not be the mixed peroxide 44.

Formaldehyde from the Reaction of 3-Bromo-2-methyl-2-butyl

Hydroperoxide (11) with Sodium Methoxide:

The reaction of 20 with base, in the manner of equation [65],

accounts for the formation of a product with an n.m.r. spectrum like

that of the glycol 14. However, to explain all the facts, a subsequent,

rapid reaction of the mixed peroxide would have to occur during which

the methoxy group became detached from the molecule and the peroxidic

link destroyed. Such a reaction is described by equation [66]. This

possibility was investigated by searching for formaldehyde.

[66]

$$HO \quad O - O - CH_2 - H$$
$$CH_3 - C - C - CH_3 \xrightarrow[CH_3OH]{CH_3O^\ominus} CH_3 - C - C - CH_3 + O = C\overset{H}{\underset{H}{}}$$
$$\underset{44}{} \qquad \underset{14}{}$$
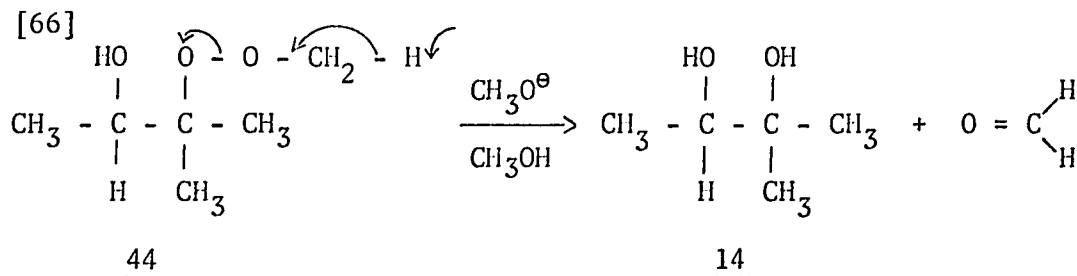
A sample of bromohydroperoxide 11 was allowed to react with base

in the manner described for the preparation of 20 for a time of 4 hours

at 0°. Nitrogen was then bubbled through the mixture at 30° in order

to sweep out the acetaldehyde and acetone which were known to be present.

After 8 hours flushing with nitrogen, formaldehyde was recovered from

the residual mixture as 1,3-diphenyltetrahydroimidazole, 4%, by adding

the residual mixture to a solution of dianilinoethane (26) in aqueous

acetic acid (117).
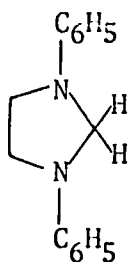
1,3-diphenyltetrahydroimidazole.

The derivative did not depress the melting point of an authentic sample (117) of 1,3-diphenyltetrahydroimidazole. In a similar experiment, but after only 4 hours flushing with nitrogen, a mixture of 1,3-diphenyl-tetrahydroimidazole, 6%, and 2-methyl-1,3-diphenyltetrahydroimidazole, 4%, was obtained. The mixture of tetrahydroimidazoles was analyzed by integrating the absorptions of the 2-protons of both derivatives in the n.m.r. spectrum. When flushing was entirely omitted the 8-hour-old reaction mixture gave only a small amount of a viscous oil when added to a solution of dianilinoethane in aqueous acetic acid (117). This oil was not examined any further.

It should be noted that although the base used in these reactions was sodium hydroxide and the solvent 90% aqueous methanol, nevertheless, the basic solution would contain a high proportion of methoxide ions. Derivatization of formaldehyde was also attempted from a reaction mixture in which methanolic sodium methoxide was used as the base, but no precipitate was obtained. Instead, during the flushing process the reaction mixture became brown in color indicating that condensation reactions had taken place.

The isolation of 1,3-diphenyltetrahydroimidazole from the reaction of 11 with methoxide ion, supports the contention that equation [66] accounts in part for the loss of peroxide content during the reaction. It is likely that most of the formaldehyde will have been used up in other side reactions. The amount of acetate ion apparently formed during the reaction was only sufficient to account for a small part of the overall process.

Reaction Between 3,3,4-Trimethyl-1,2-dioxetane (20) and Sodium
Methoxide:

In the above reactions the possibility existed that unreacted
starting material, 11, might have influenced the course of the reaction
of 20 with base. To investigate this possibility a study was made of
the reaction between a benzene solution of 20 and methanolic sodium
methoxide. At 35°, a small volume of 0.68 M 20 in benzene was diluted
with twice its volume of methanol-d_4 containing one equivalent of
dissolved sodium methoxide-d_3. The reaction was followed by n.m.r.
spectroscopy. When the slow reaction had ceased (ca. 3 hours) the
final spectrum resembled those obtained in the reaction of the
bromohydroperoxide, 11, with methanolic sodium methoxide (Figures 12e,f).
As before, (Figures 12e,f), there was no evidence in the n.m.r. spectrum
of this solution to indicate that any allylic hydroperoxide had been
formed in the reaction. Furthermore, at the end of the reaction the
peroxide content had fallen to zero.

Reaction between 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) and
Aqueous Sodium Hydroxide:

This reaction was investigated in order to ascertain the effect
of solvent polarity on the behavior of the 1,2-dioxetane, 20, towards
base.

A quantity of bromohydroperoxide 11 slowly dissolved into a
four-fold excess of 1 M aqueous sodium hydroxide at 0°. Samples were
withdrawn at intervals and titrated for total peroxide content (30).
After 90 minutes, when the mixture had become homogeneous, 73% of the

total peroxide remained. After 120 minutes reaction, the total peroxide content was still 67% of the initial value. After 150 minutes reaction, one estimation for liberated bromide ion showed that 98% of the starting 11 had reacted. After a further 21 hour reaction at 0°, when the peroxide content had fallen to 18% of the initial value, sodium borohydride was added to the mixture to reduce the residual peroxide. After a further 21 hours the mixture was continuously extracted with ether. The dried organic fraction was concentrated and the residual oil quantitatively analyzed by g.l.c. (13) using benzonitrile as internal standard. The major products, 2-methyl-1-buten-3-ol (45), 2-methyl-2,3-butanediol (14) and 2-methyl-1-buten-3-one (46) were identified by comparison of their g.l.c. retention times with those of authentic samples of 45, 14 and 46. In addition, 14 and 45 were collected from the effluent of the g.l.c. column and identified spectroscopically. Based on the peroxide content of the starting material, 11, the yields of products were 45, 27%, 14, 23%, and 46, 7.5%. There was no evidence for the presence of 3-methyl-1-buten-3-ol (47) in the g.l.c. chromatogram, proving that allylic hydroperoxides are not formed by direct elimination of the elements of halogen acid.

The residual oil was also subjected to g.l.c. analysis at low temperature. The most abundant volatile product was acetone, ca. 6%. Only traces of other products were observed. The results are summarized in equation [67].

[67]

11   47

45 (27%)   46 (7.5%)

14 (23%)   6%

The formation of 46 during the reaction is presumably due to base-catalyzed carbonyl-forming elimination (16) of the elements of water from the allylic hydroperoxide, 48, eq. [68].

[68]

48   46

Elimination reactions of this type are commonly observed to occur with benzilic hydroperoxides (16,118) and are expected for allylic

hydroperoxides. Assuming that the glycol, 14, and the allylic alcohol, 45, were formed by reduction of the corresponding hydroperoxides, then it is necessary to explain why the peroxide titer before reduction was so much smaller (18%) than the combined yield of 14 and 45 (50%). This observation suggests that some of the initially formed hydroperoxides had already been reduced prior to the addition of sodium borohydride.

In 1898, Blank and Finkenbiemer reported (119) that formaldehyde was rapidly oxidized to formate ion in the presence of alkaline hydrogen peroxide, eq. [69].

$$[69] \quad \begin{array}{c} H \\ \diagdown \\ \diagup \\ H \end{array} C = O \quad + \quad H - O - O^{\ominus} \quad \xrightarrow[\text{3 minutes}]{25°} \quad H - \underset{\underset{O}{\parallel}}{C} - O^{\ominus} \quad + \quad H_2O$$
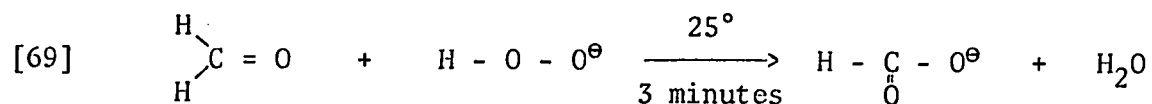
The same authors also reported (119) that acetaldehyde underwent a similar reaction, but at a slower rate. In the reactions of 11 or 20 with base, the acetaldehyde produced by thermal decomposition of 20 could conceivably be oxidized by any one of a number of hydroperoxides present during the reaction, eq. [70].

$$[70] \quad R - O - O^{\ominus} \quad + \quad CH_3 - \underset{\underset{O}{\parallel}}{C} - H \quad \longrightarrow R - OH \quad + \quad CH_3 - \underset{\underset{O}{\parallel}}{C} - O^{-}$$
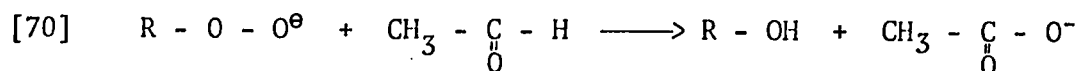
Similar reactions could also account for the large amounts of bromohydrins, and hence epoxides, formed in the preliminary experiments described in Chapter I. However, in a test of this possibility, using alkaline t-butyl hydroperoxide and benzaldehyde, no reaction was observed during a period of 20 hours at 5°. The failure of this test indicates that the Blank and Finkenbiemer reaction (119) is not

completely general. However, the failure to react may be a property of tertiary peroxides, and cannot be excluded as a possible mode of reduction in other cases.

The formation of some allylic hydroperoxide from 11 in aqueous base is in agreement with the observations of van de Sande (4), but contrasts sharply with the course of the same reaction in methanolic base. It appeared from this experiment that either the 1,2-dioxetane 20 behaved differently in aqueous solution, or that allylic hydroperoxides are formed by a different route, not involving 1,2-dioxetanes, which only operates in polar solvents. The allylic hydroperoxide, 48, formed in the reaction, has the hydroperoxy group on the secondary carbon atom instead of the tertiary carbon as was the case in the bromohydroperoxide, 11. Evidence of such an exchange of the hydroperoxy group led van de Sande to conclude (4) that an intermediate 1,2-dioxetane was involved during the formation of allylic hydroperoxides from the reaction of bromohydroperoxides with base. In Chapter IV evidence is presented to show that 1,2-dioxetanes are not the precursors to allylic hydroperoxides.

EXPERIMENTAL

Reaction Between 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) and

Sodium Methoxide:

(a) Spectroscopic Study.

A sample of 11 (0.406 g, 90.2% pure, 0.002 mole) contained in a

5 ml flask was cooled with stirring to 0°. Then base was slowly added,

consisting of 0.078 g, 1.7 equivalents, of sodium metal dissolved in

2.0 ml of methanol-d_4. As soon as possible a sample of the mixture

was transferred to an ice-cooled n.m.r. tube by means of an ice-cold

syringe. N.m.r. spectra of the mixture, recorded at 0°, are shown in

Figures 12a-c. The spectra have been described in the results and

discussion section.

(b) Rate of Loss of Total Peroxide.

The above reaction was repeated on a 10-fold scale using methanol

in place of methanol-d_4. As soon as possible 2 ml aliquots of the

mixture were removed, quenched with 20 ml of 3:2 acetic acid-chloroform

mixture, and estimated for total peroxide (30) by titration with a

0.20 M aqueous sodium thiosulfate. The decline of peroxide

concentration with time during this reaction is shown in Figure 13.

After 20 hours, the n.m.r. spectrum of the solution was recorded.

The spectrum obtained, shown in Figure 12f, has been described in the

results and discussion section. The reaction was repeated and allowed

to run for 4 hours. At this time, nitrogen was bubbled through the

solution and the volatile materials collected in a Dry Ice-acetone

trap. The volatile materials, acetone, acetaldehyde and methanol, were identified by g.l.c. analysis. There was no evidence in the g.l.c. chromatogram to suggest the presence of methyl acetate.

Flushing with nitrogen was continued until all the solvent had evaporated. The residue was dissolved in carbon tetrachloride and again evaporated. This process was repeated a further two times. The sticky solid remaining was shaken with carbon tetrachloride for 30 minutes. The solution obtained gave an n.m.r. spectrum identical with that of 2-methyl-2,3-butanediol (14). The undissolved material was taken up in deuterium oxide and the n.m.r. spectrum of the resulting solution recorded. The major component of the mixture was again 14, but in addition a relatively small peak (singlet) was observed at τ 8.0 (external TMS). A solution of sodium acetate in deuterium oxide also absorbed at this position in the n.m.r. spectrum.

The Reaction of Acetaldehyde with Methanol:

The n.m.r. spectrum (methanol) of acetaldehyde showed absorption at τ 8.76 (doublet, J = 5.0 c.p.s.) due to the methyl group of acetaldehyde hemiacetal. Any other peaks were obscured by solvent absorptions.

The Reaction between Acetone, Acetaldehyde and Methanolic Sodium Methoxide:

A mixture of acetone (5.8 g, 0.1 mole) and acetaldehyde (4.4 g, 0.1 mole) was added to 100 ml of 1.0 M sodium methoxide in methanol at 0°. When n.m.r. spectra of this mixture were recorded at 0°, absorption was observed at τ 5.02 (quartet, J = 5.0 c.p.s.),

τ 7.83 (singlet) and τ 8.75 (doublet, J = 5.0 c.p.s.). These absorptions were due to acetaldehyde hemiacetal, τ 5.02 and τ 8.76, and acetone, τ 7.83. When the spectrum was recorded at 35° the initial spectrum was identical with that observed at 0°, but a series of very rapid changes occurred. Within four minutes the quartet at τ 5.02 had disappeared and the doublet at τ 8.76 became a multiplet with maxima at τ 8.73, 8.78, 8.82, 8.89 and 8.93. These changes are assumed to be due to condensation reactions.

Formaldehyde from the Reaction Between 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) and Sodium Methoxide:

A sample of 11 (2.00 g, 91.3% pure, 0.01 mole) was cooled with stirring to 0°. Then a solution of sodium methoxide, prepared by dissolving sodium metal (0.195 g, 0.017 mole) in 5 ml methanol, was slowly added. After 8 hours reaction at 0°, nitrogen was passed through the solution at room temperature. The volatile materials were collected in a cold trap. After four hours flushing neither the collected volatile materials, nor the brown residue gave any precipitate with a solution of dianilinoethane (26) in 2:3 acetic acid-water mixture (117). The experiment was repeated under different conditions.

A solution of 11 (2.00 g, 91.3% pure, 0.01 mole) in 6 ml methanol was allowed to react with sodium hydroxide (0.44 g, 0.011 mole) dissolved in 4 ml of 75% aqueous methanol at 0°. After four hours reaction, nitrogen was swept through the solution at room temperature for 8 hours. The volatile materials were swept into a trap consisting of a solution of dianilinoethane (26) in aqueous acetic acid (117).

No precipitate was obtained in the trap, but the involatile material
remaining gave an immediate precipitate of 1,3-diphenyltetrahydro-
imidazole, 0.091 g, 4%, (based on the hydroperoxide content of $\underline{11}$),
m.p. 120.5°. Authentic 1,3-diphenyltetrahydroimidazole was prepared
by reacting formaldehyde (0.82 ml, 36.6% aqueous solution, 0.01 mole)
with 2.12 g (0.01 mole) of dianilinoethane (26) in 250 ml of 2:3
acetic acid-water mixture (117). The authentic material, recovered in
73% yield, melted at 121°. A mixture of both samples melted at 120.5°.
In a duplicate experiment, with only four hours purging with nitrogen,
0.23 g of a mixture of 1,3-diphenyltetrahydroimidazole and 2-methyl-
1,3-diphenyltetrahydroimidazole, m.p. 70-90°, was recovered when the
residue was added to a solution of dianilinoethane (26) in aqueous
acetic acid (117). The components of the mixture were identified by
comparison of the n.m.r. spectrum (CCl_4) of the mixture with those of
authentic samples of the two imidazoles (117). In carbon tetrachloride,
the 2-protons of 1,3-diphenyltetrahydroimidazole appeared at τ 5.41
(singlet), while the 2-proton of 2-methyl-1,3-diphenyltetrahydroimidazole
appeared at τ 4.62 (quartet) in the n.m.r. spectrum. From the
integration of these protons in the n.m.r. spectrum of the mixture,
the molar ratio of formaldehyde to acetaldehyde derivative was
estimated to be 6:4. The yields of the recovered aldehydes were
formaldehyde 6%, and acetaldehyde 4%. When purging with nitrogen
was omitted, the entire reaction mixture gave only a small amount of
an oil when added to a solution of dianilinoethane (26) in aqueous
acetic acid (117). The oil was not examined further.

Reaction Between 3,3,4-Trimethyl-1,2-dioxetane (20) and Sodium
Methoxide:

To 0.5 ml of a solution of 0.68 M 20 in benzene was added 1.0 ml
of 0.34 M sodium methoxide-d_3 in methanol-d_4, prepared by dissolving
0.0078 g of sodium metal in 1.0 ml of methanol-d_4. The resulting
mixture was ca. 0.23 M in each reactant. The n.m.r. spectrum of the
mixture was recorded at an operating temperature of 35°. After 2 hours
reaction at 35° followed by standing overnight the final spectrum was
virtually identical with that obtained from the reaction of the
bromohydroperoxide 11 and base (Figures 12e,f). There was no
indication of any olefinic absorption in the n.m.r. spectrum. The
final mixture obtained, failed to liberate iodine on treatment with
acidified potassium iodide.

Reaction Between 3-Bromo-2-methyl-2-butyl Hydroperoxide (11) and
Aqueous Sodium Hydroxide:

A sample of 11 (5.0 g, 91.4% pure, 0.025 mole) was added with
stirring to 100 ml of 1.0 M aqueous sodium hydroxide at 0°. After 90
minutes, when the mixture had become homogeneous, a 10 ml sample was
withdrawn and titrated for total peroxide content (30). The peroxide
content had fallen to 73% of the calculated initial value. After 120
minutes the peroxide content was 67% of the initial value, while after
150 minutes, titration for liberated bromide ion showed that 98% of the
starting material, 11, had been consumed. The total peroxide content
fell to 18% of the initial value after 24 hours. The reaction was
then repeated but without removing any samples for titration. After
24 hours at 0° the mixture was treated with excess sodium borohydride

(0.27 g, 7 x 10^{-3} mole). After a further 21 hours the mixture was continuously extracted with ether. The dried organic layer was concentrated by distillating off the solvent through a 4 ft. Podbielniak column. The residual oil was examined by n.m.r. spectroscopy. Apart from some ether absorption, the n.m.r. spectrum showed the presence of the glycol, 14, and some olefinic absorption. The oil was then analyzed by g.l.c. on a 5 ft. x 1/4 in. column of Q.F. 1 at 90°. The chromatogram showed the presence of two major products and a minor constituent. The peak of longest retention time was collected from the effluent of the g.l.c. column. The n.m.r. and infrared spectra of the collected material were identical with those of the glycol, 14. The other two products could only be collected as a mixture. The n.m.r. spectrum of this mixture contained all the peaks due to absorption by 2-methyl-1-buten-3-ol (47) the major component, and 2-methyl-1-buten-3-one (46). In addition, all three products were identified by comparison of their retention times on g.l.c. analysis, with those of authentic samples of 14, 47 and 46. Quantitative analysis (13) on the same column using benzonitrile as internal standard showed that the compounds 14, 47, and 46 had been formed in the reaction, in yields of 23%, 27%, and 7.5%, respectively. The molar response factors of 14, 47, and 46 were found to be 93, 90, and 87, respectively, relative to benzonitrile, 100 units. G.l.c. analysis of the mixture on a 5 ft. x 1/4 in. column of 15% FFAP at 65° permitted separation of the more volatile products. The only peak of any significance due to volatile materials was identified as acetone by comparison of its retention time on g.l.c. analysis with that of authentic material.

The yield of acetone was ca. 6%. The product imbalance, 36%, is assumed to be due to loss of cleavage products, acetone and acetaldehyde, during the reaction and subsequent work-up.

2-Methyl-1-buten-3-one (46):

A 2 l three-necked flask, containing 950 ml water and 40 ml concentrated sulphuric acid, was fitted with a mechanical stirrer reflux condenser, thermometer and dropping funnel. The mixture was heated to 60° and 25 g of red mercuric oxide was added. When the mercuric oxide had dissolved, 3-hydroxy-3-methyl-1-butyne (168 g, 2.0 mole) was added drop-wise over a period of 1.5 hours at such a rate as to hold the temperature at 60°. The mixture was stirred for a further 10 minutes at the end of the addition and then cooled to room temperature. The homogeneous solution was then made saturated with anhydrous sodium sulfate. The oil which separated was taken up in 750 ml ether and the aqueous layer extracted four times with 250 ml quantities of ether. The combined ether extracts were washed once with 500 ml of saturated aqueous sodium chloride solution and dried over anhydrous sodium sulfate. The solvent was removed and the dried product distilled through a 15 cm vigreaux column, b.p. 137-138.5° (705 mm) $n_D^{26} = 1.4136$; reported (120) b.p. 140-141°, $n_D^{21} = 1.415$. The yield of 3-hydroxy-3-methyl-2-butanone was 128.3 g, 63%. If the reaction mixture was not made saturated with sodium sulfate the yield was only 42.5%.

A mixture of 3-hydroxy-3-methyl-2-butanone (49.5 g, 0.485 mole), anhydrous sodium acetate (25 g) and acetic anhydride (100 g, 1 mole)

was heated under reflux for six hours (121). The mixture was then

cooled and poured into 600 ml water and neutralized with solid sodium

carbonate. The oil which separated was taken up in 500 ml ether,

washed once with saturated sodium chloride solution and dried. The

solvent was removed and the residue distilled through a 15 cm vigreaux

column. The colorless distillate, 3-acetoxy-3-methyl-2-butanone, was

obtained in 84% yield (58.9 g), b.p. 171-171.8° (698 mm), n_D^{24} = 1.4178;

reported (121) b.p. 93° (50 mm), n_D^{20} = 1.4180. This material was

pyrolyzed at 460-470° following the procedure of McMahon and co-workers

(122). From 49.1 g of 3-acetoxy-3-methyl-2-butanone there was obtained

46.9 g of pyrolysate. The pyrolysate was dissolved in 100 ml isopentane

and cooled when acetic acid (18 g, 96% yield), was obtained as crystals.

The mixture was filtered and the filtrate fractionally distilled.

There was obtained 15.2 g (56%) of 2-methyl-1-buten-3-one (46), b.p.

94.5-95.5° (700 mm), n_D^{25} = 1.4196; reported (122) b.p. 38° (85 mm),

n_D^{20} = 1.4235. The n.m.r. spectrum (CCl_4) showed absorption at τ 4.10

and τ 4.26 (unresolved multiplets) due to the vinyl protons, τ 7.75

(singlet) attributed to the terminal methyl group and τ 8.20

(unresolved multiplet) attributed to the allylic methyl group. G.l.c.

and n.m.r. analysis of the product showed the presence of ca. 5% of

an impurity.

2-Methyl-1-buten-3-ol (45):

Aluminum hydride (3.7 x 10^{-3} mole) in ether was prepared (123)

by adding aluminum chloride (1.22 g, 9.2 x 10^{-3} mole) to a cooled

suspension of lithium aluminum hydride (1.044 g, 2.75 x 10^{-2} mole) in

100 ml ether. Then a solution of 2-methyl-1-buten-3-one (46) (8.4 g,
0.1 mole) in 80 ml ether was added during a period of 20 minutes.
After 2 hours, 15% aqueous potassium hydroxide was added until the
organic layer became clear. The ether layer was separated by
decantation and dried. The solvent was then removed and the residue
fractionated. There was obtained 1.9 g (22%) of 2-methyl-1-buten-3-ol
(45), b.p. 112.5-115.5° (705 mm), n_D^{25} = 1.4242; reported (124) b.p.
112-113° (700 mm), n_D^{21} = 1.4296. The n.m.r. spectrum (CCl_4) of the
product showed absorption at τ 5.11 and τ 5.30 (unresolved multiplets)
due to the vinyl protons, τ 5.87 (quartet, J = 6.5 c.p.s.) due to the
methine proton, τ 6.80 (singlet) due to the hydroxyl group proton,
τ 8.76 (unresolved multiplet) due to the allylic methyl group and
τ 8.89 (doublet, J = 6.5 c.p.s.) of the terminal methyl group.

Lack of Reaction between t-Butyl Hydroperoxide, Benzaldehyde and
Sodium Methoxide:

Redistilled t-butyl hydroperoxide (0.9 g, 0.01 mole) was dissolved
in 10 ml of methanol and cooled to 0°. Then base was added consisting
of sodium hydroxide (0.44 g, 0.011 mole), 12 ml methanol and 1.5 ml
water. The mixture was kept at 0° for a total of 19 hours. Known
fractions of the mixture were titrated for total peroxide at intervals.
The total peroxide content remained constant at 93% of the expected
level throughout this period.

CHAPTER IV

THE BASE-PROMOTED REACTIONS OF TETRASUBSTITUTED

β-HALOHYDROPEROXIDES

van de Sande has proposed that the reaction between

tetrasubstituted β-halohydroperoxides and base leads initially to

the formation of tetrasubstituted 1,2-dioxetanes (4). These

intermediates were said to react very rapidly with base to form

allylic hydroperoxides (4), eq. [71]. Evidence (4) for the

[71]
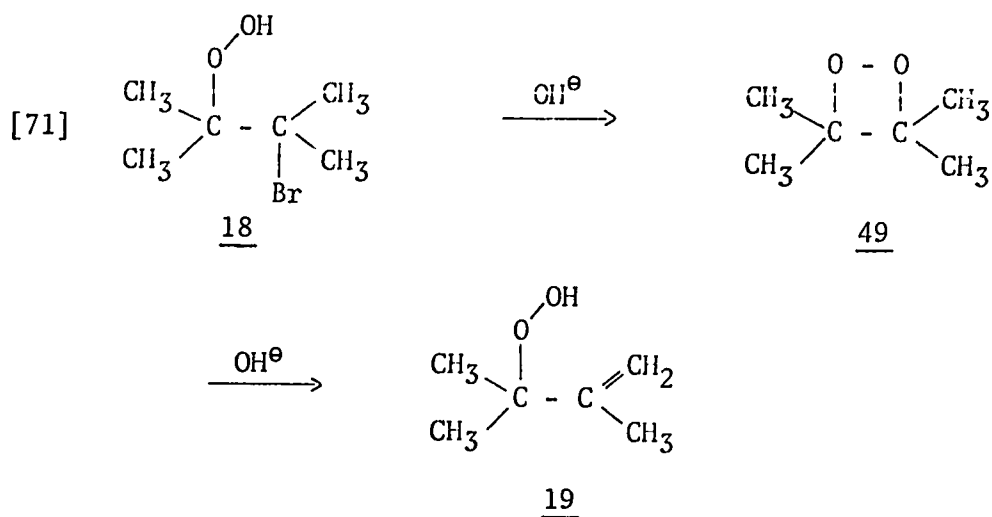
formation of a symmetrical intermediate during the reaction, included

observation of a transient twelve proton peak in the n.m.r. spectrum

of the mixture, and detection of exchange of the hydroperoxy group

between the two tertiary carbon atoms. Thus, a mixture of deuterated

3-bromo-2,3-dimethyl-2-butyl hydroperoxides were converted by base to

a mixture of deuterated 2,3-dimethyl-3-hydroperoxy-1-butenes in which

the ratio of isomers had undergone inversion, eq. [72] (4).

[72]

$$\begin{array}{ccc}
\underset{CD_3}{\overset{CD_3}{\diagdown}}C - C\underset{CH_3}{\overset{CH_3}{\diagdown}}Br & + & \underset{CD_3}{\overset{CD_3}{\diagdown}}Br-C - C\underset{CH_3}{\overset{CH_3}{\diagdown}}OOH \\
40\% & & 60\%
\end{array}$$

$$OH^{\ominus} \Big| 0°$$

$$\begin{array}{ccc}
\underset{CD_3}{\overset{CD_3}{\diagdown}}HOO-C - C\underset{CH_3}{\overset{CH_2}{\diagup}} & + & \underset{CD_3}{\overset{CD_2}{\diagup}}C - C\underset{CH_3}{\overset{CH_3}{\diagdown}}OOH \\
69\% & & 31\%
\end{array}$$
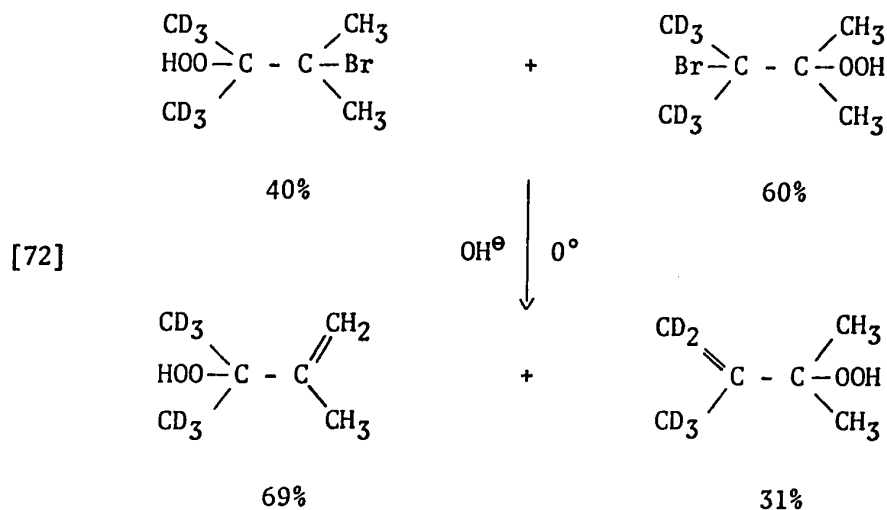
The possibility that 1,2-dioxetanes were not the precursors of allylic hydroperoxides was not considered by van de Sande (4), however, two other mechanistic routes to allylic hydroperoxides can be envisaged. One of these proposed mechanisms involves an initial fragmentation reaction (125) eq. [73]. The fragmentation products,

[73]

$$\begin{array}{c} 18 \end{array}$$

$$\begin{array}{c} \underline{19} \end{array}$$
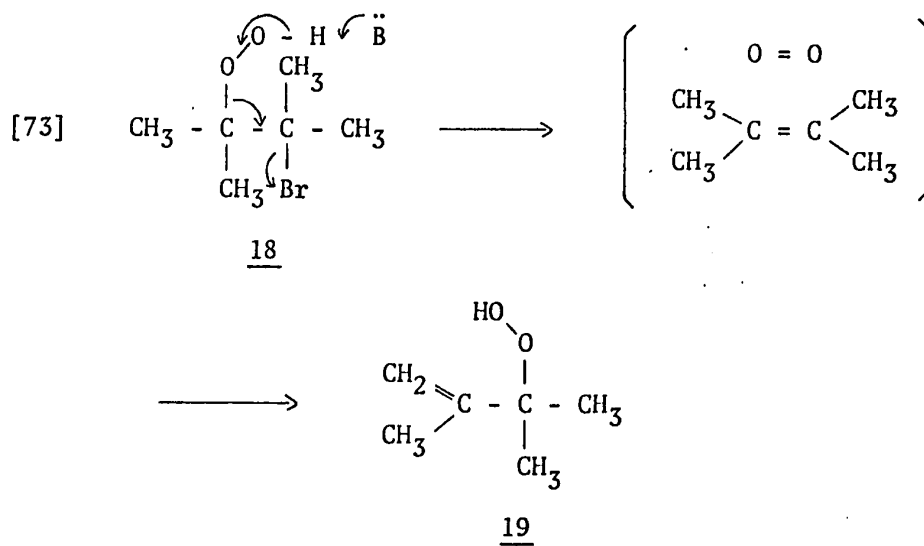
singlet oxygen and tetramethylethylene, would be expected to react

instantly within the associated solvent cage to give the allylic

hydroperoxide, 19, because these species are known to react at a

diffusion controlled rate (126).

The other mechanism to be considered involves the intermediacy of

a perepoxide, eq. [74].
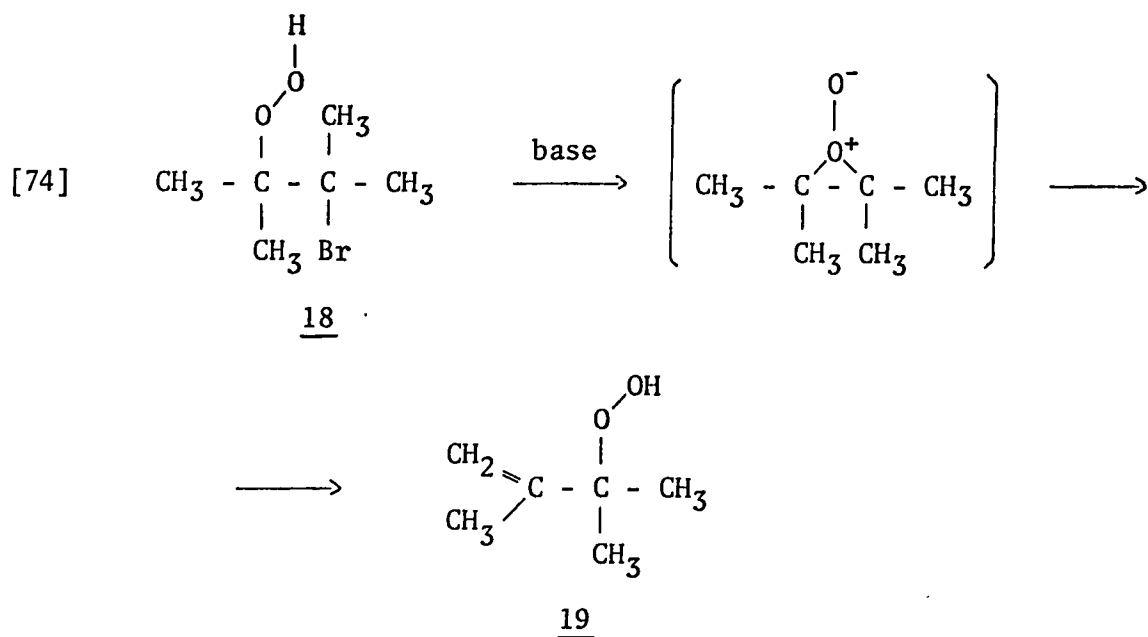
Perepoxides have been proposed as intermediates in the dye-sensitized

photooxygenation of olefins (3,127), but this possibility now seems

quite remote (111). In the present case, however, a perepoxide

intermediate would account for exchange of the hydroperoxy group

between the tertiary carbon atoms, might be observable in the n.m.r.

spectrum of the reaction mixture and should undergo rapid proton

transfer to give an allylic hydroperoxide. Such a dipolar intermediate

would be stabilized by electron donation from methyl or phenyl

substitution, and its formation would be more highly favored when polar

solvents were used. The operation of these latter effects could account for the differences in reaction between tetrasubstituted and trisubstituted β-halohydroperoxides, and the effect of solvent polarity on the base-promoted reactions of 3-bromo-2-methyl-2-butyl hydroperoxide (11) (Chapter III).

The work in this chapter was designed to differentiate between the above mechanisms. The synthesis of 3,3,4,4-tetramethyl-1,2-dioxetane (49) was achieved. Compound 49 did not react with base to give 2,3-dimethyl-3-hydroperoxy-1-butene (19).

RESULTS AND DISCUSSION

Isolation of 3,3,4,4-Tetramethyl-1,2-dioxetane (49):

Because there seemed little hope of isolating 3,3,4,4-tetramethyl-1,2-dioxetane (49) from the reaction of 3-bromo-2,3-dimethyl-2-butyl hydroperoxide (18) with base, van de Sande tried to synthesize 49 by treating 18 with silver tetrafluoroborate. Kirschke (21) attempted the same synthesis using silver perchlorate. The only product reported by either worker was acetone (4,21). It seemed likely that the strong acids produced in these reactions would catalyze the decomposition of any 49 that was formed, eq. [75], so that these syntheses were doomed to failure.

[75]

$$CH_3 - \overset{\overset{\displaystyle 0\nearrow\overset{\oplus}{0}\diagdown{}^H}{|}}{\underset{\underset{CH_3}{|}}{C}} \overset{|}{\underset{\underset{CH_3}{|}}{C}} - CH_3 \longrightarrow \underset{CH_3 \quad CH_3}{\overset{\overset{\displaystyle O}{\parallel}}{C}} + \underset{CH_3 \quad CH_3}{\overset{\overset{\displaystyle OH}{|}}{C^{\oplus}}} \longrightarrow 2 \; \underset{CH_3}{\overset{CH_3}{\diagup}} C = O$$

49
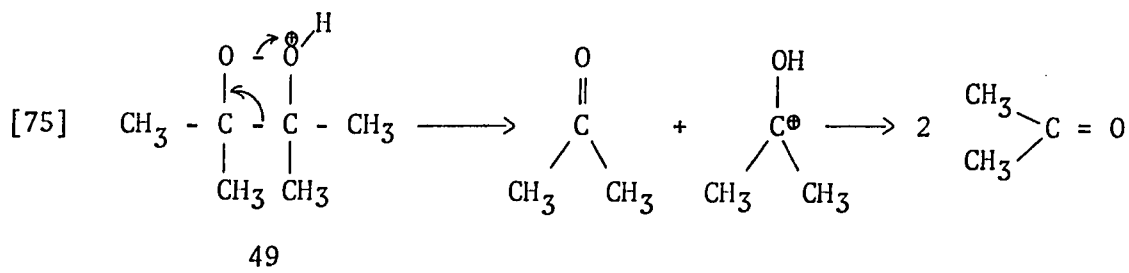
Use of silver acetate seemed more reasonable because the acetic acid produced would be far less likely to catalyze the decomposition of 49. Since silver salts are known to be slightly soluble in benzene (128) it was decided to use benzene as the reaction medium.

A rapid reaction occurred when 3-bromo-2,3-dimethyl-2-butyl hydroperoxide (18) was shaken with a suspension of silver acetate powder in benzene at room temperature. After 30 minutes reaction, the

resulting mixture was filtered to give a yellow precipitate of silver

bromide. The yellow filtrate was subjected to n.m.r. spectroscopic

analysis. The n.m.r. spectrum (benzene) showed absorption at τ 5.07

and τ 5.17 (multiplets) due to the vinyl protons, τ 8.24 (singlet) due

to the allylic methyl group, and τ 8.76 (singlet) due to the gem-

dimethyl groups of 2,3-dimethyl-3-hydroperoxy-1-butene (19). In

addition the spectrum showed absorption at τ 8.39 (singlet) due to

acetic acid (and perhaps a trace of acetone), τ 8.83 (singlet) due to

the 1,2-dioxetane 49, and a relatively small absorption at τ 9.13

(singlet) of unknown origin. From the integration of the peaks at

τ 8.76 (6H) of 19 and τ 8.83 (12H) of 49, the ratio of 19: 49 was

estimated to be 4:1. The acetic acid and perhaps acetone were removed

by washing with water. The allylic hydroperoxide, 19, was removed by

repeated washing with aqueous sodium hydroxide. The yield of recovered

19, 30%, was estimated, by iodimetric titration (30) of the aqueous

extracts. The remaining products were isolated as a mixture of liquid

and crystals by removing the benzene under reduced pressure. The

residue was recrystallized twice from pentane at -20° and then sublimed

to give yellow, rectangular plates. This material was identified as

3,3,4,4-tetramethyl-1,2-dioxetane (49). The yield of purified 49 was

only 3-6% in a number of preparations. The dioxetane was quite volatile,

often subliming to another part of the sample tube even when stored at

-10°. In this respect the material resembled pinacol. The dioxetane

rapidly gave iodine on treatment with potassium iodide and acetic acid.

The dioxetane melted at 76-77° to give a liquid which emitted a faint

blue luminescence. The n.m.r. spectrum of the dioxetane showed a

singlet absorption at τ 8.83 (benzene) and τ 8.58 (CCl$_4$). In addition,

the n.m.r. spectrum of 49 was recorded at low temperature using fluoro-

trichloromethane as solvent. The spectra obtained at -40°, -70° and

-90°, all showed a singlet absorption at τ 8.55 with a peak-width at

half-height of 1.9 c.p.s. The lack of splitting of the singlet at low

temperature suggests that the two bent forms of the ring undergo rapid

interconversion (129):
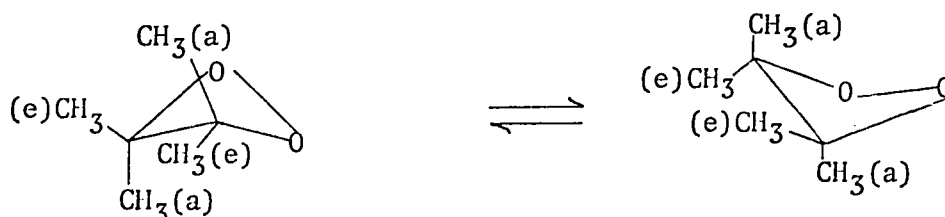
The infrared spectrum of the peroxide (CCl$_4$) showed absorption

at 1380 and 1370 cm^{-1} due to the gem-dimethyl groups, 1202 and 1168 cm^{-1}

attributed to the C - O stretching frequencies and 868 cm^{-1} attributed

to the O - O stretching frequency. These peaks had counterparts in the

absorption spectrum of 3,3,4-trimethyl-1,2-dioxetane (20). There was

no evidence for hydroxyl or carbonyl absorption in the spectrum.

The Molecular Weight of 3,3,4,4-Tetramethyl-1,2-dioxetane (49):

As described in Chapter II, it had not been possible to measure

the molecular weight of 3,3,4-trimethyl-1,2-dioxetane (20) so that

some uncertainty remained as to whether the substance, 20, was

monomeric or dimeric. It became of vital importance to establish the

composition and molecular weight of 49, and then relate the properties

of 49 to those of 20. A monomeric composition for 49 was established

in several ways:

(a) Mass Spectrum of 3,3,4,4-Tetramethyl-1,2-dioxetane (49).

The mass spectrum of 49 was obtained with difficulty. No conditions were established under which the mass spectrum could be obtained consistently. A good mass spectrum was obtained using the MS-12 mass spectrometer with a water cooled source and direct insertion of the sample. The ionization potential was maintained at 70 volts. Under these conditions strong peaks were observed at m/e 116, 84(M-32), 69(M-47), 58(M-58) and 43(M-73). The parent peak, m/e 116, corresponds to $C_6H_{12}O_2$. There was no peak at m/e 232. The most prominent peak in all the spectra was at m/e 58 which corresponds to acetone. Most of the spectra showed no peaks beyond m/e 58. The peaks at m/e 84 and 69 are also present in the mass spectrum of 2,3-dimethyl-2-butene (4). The peak at m/e 43 is present in the mass spectrum of acetone, where it appears as the base peak (130).

(b) Osmometry.

An attempt was made to determine the molecular weight of 49 using a Mechrolab Vapour Pressure Osmometer, Model 301A, with benzene as solvent. The temperature of the apparatus, 32.5°, was not felt to be a serious threat to the success of the molecular weight determination. However, the operator reported that the molarity of the solution changed continuously so that no determination was possible. Examination of the procedure used, revealed that the solution under test is transferred from a metal syringe to a metallic thermistor during the determination. It seemed probable that contact with these metallic surfaces was causing the peroxide to decompose so the method was discontinued.

(c) Freezing point Depression.

The molecular weight of 49 was readily determined by the method of freezing point depression (131). The technique has the advantage that an all-glass apparatus can be used. Furthermore, by using benzene as the solvent the determination could be carried out at ca. 6°. In the determination, 0.0878 g of 49 dissolved in 12.50 g of benzene, depressed the freezing point of benzene by 0.332°. The cryoscopic constant of the solvent was determined to be 5313, using napthalene as standard. The molecular weight of 49 was calculated using equation [76] (131).

$$[76] \qquad\qquad m = \frac{K_f w}{\Delta T W}$$

In this equation "m" is the desired molecular weight, K_f the cryoscopic constant of the solvent, ΔT the freezing point depression caused by dissolving w g of solute in W g of solvent. The molecular weight of 49 was found to be 112.4; required 116.16 for the monomer.

Thermal Decomposition of 3,3,4,4-Tetramethyl-1,2-dioxetane (49):

A solution of 49 in benzene was subjected to g.l.c. analysis at 65°. Only one product peak was observed with retention time identical with that of acetone. The yield of acetone from the decomposition of 49 was measured using n.m.r. spectroscopy, by heating a benzene solution of 49 in a sealed n.m.r. tube with anisole as internal standard. By comparing the average of six integrations of the peaks due to the methoxyl group of anisole (τ 6.68) and 49 (τ 8.83), before

heating at 70° overnight, with that of anisole and acetone (τ 8.39) after heating, the yield of acetone was estimated to be 96 ± 6%.

Luminescence in the Thermal Decomposition of 3,3,4,4-Tetramethyl-1, 2-dioxetane (49):

By analogy with 3,3,4-trimethyl-1,2-dioxetane (20) it was expected that 49 would emit light during decomposition.

A faint bluish-white luminescence was observed when solutions of 49 in benzene were heated to 70°. Similarly, a bright green glow was observed when a benzene solution of 49 containing pyrene was heated above 70°. This experiment provided another link between the two 1,2-dioxetanes described in this work, and supports the monomeric composition which was assigned to 3,3,4-trimethyl-1,2-dioxetane (20). By analogy with compound 20 it maybe assumed that the thermal decomposition of 49 gives rise to the formation of excited singlet acetone. Consequently, compound 49 is inherently more useful as a source of photochemical energy than is 20, because the nature of the excited species from 49 is known with greater certainty.

Lack of Reaction Between 3,3,4,4-Tetramethyl-1,2-dioxetane (49) and Methanolic Sodium Methoxide:

A methanol solution ca. 0.11 M in 49 and 0.11 M in sodium methoxide showed a singlet, solute absorption at τ 8.51 in the n.m.r. spectrum. van de Sande has reported (4) that the intermediate formed during the reaction of the bromohydroperoxide, 18, with methanolic sodium methoxide, absorbs at τ 8.67 in the n.m.r. spectrum, so that 49 can be excluded as an intermediate in that reaction.

After 90 minutes at 35° there was no indication that any of 2,3-dimethyl-3-hydroperoxy-1-butene (19) or pinacol had been formed in the reaction of 49 with sodium methoxide. Instead, the only new absorption appeared at τ 8.74 which corresponded to the position of absorption of acetone in this solvent. Acetone could arise by the thermal decomposition of 49.

This experiment proved that 1,2-dioxetanes are not the precursors of allylic hydroperoxides in the reaction of tetrasubstituted β-halohydroperoxides with base or in the reaction of olefins with singlet oxygen.

The failure to observe pinacol formation in the above reaction shows that 49 is even less reactive towards base than is 3,3,4-trimethyl-1,2-dioxetane (20), which slowly gave 2-methyl-2,3-butanediol (14) under similar reaction conditions.

Deciding which of the other two mechanisms is involved in allylic hydroperoxide formation is considerably more difficult.

Thermochemical considerations show that the fragmentation reaction is far less exothermic than 1,2-dioxetane formation, eq. [77].

[77]
$$CH_3 - C(CH_3)(OOH) - C(CH_3)(CH_3)Br + OH^{\ominus}$$

(structure 18)

$$\xrightarrow{a} \quad (CH_3)_2C = C(CH_3)_2 \text{ with } O = O \quad + Br^{\ominus}$$

$$\xrightarrow{b} \quad (CH_3)_2C - C(CH_3)_2 \text{ with } O - O \text{ (structure 49)} \quad + H_2O .$$
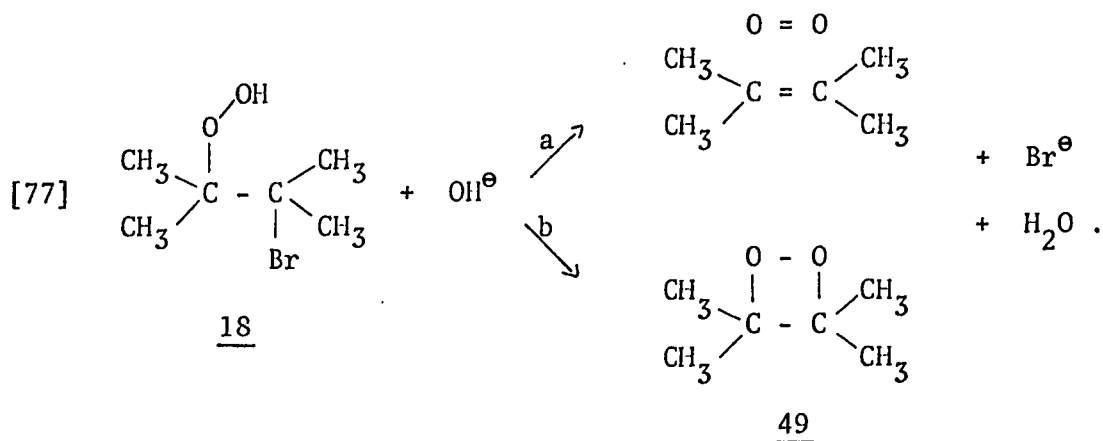
Both reaction pathways commence with the same reactants and both give water and bromide ion as reaction products. However, pathway "b", eq. [77], is considerably more exothermic because the free energy of formation of the 1,2-dioxetane, 49, is much lower than that of 2,3-dimethyl-2-butene and singlet oxygen combined. The heat of formation of 3,3,4,4-tetramethyl-1,2-dioxetane (49) is estimated to be -30 kcal mole^{-1} (53), while the combined heats of formation of singlet oxygen and tetramethylethylene are estimated (53) to be +6.4 kcal mole^{-1}. The heat of formation of singlet oxygen was assumed to be 22.5 kcal mole^{-1} (132). Thus, in equation [77], pathway "b" would be ca. 40 kcal mole^{-1} more exothermoic than path "a", so that pathway "b" would be energetically more favorable.

van de Sande has studied the kinetics of the reaction between 2-bromo-2,3-dimethyl-3-butyl hydroperoxide (18) and base. He observed (4) that the reaction obeyed second order kinetics, with an activation energy of 7.6 ± 1.0 kcal mole^{-1} and an entropy of activation $\Delta S^{\#}$ = -46 ± 5 e.u. The large, negative entropy of activation implies that there is an increase in rigidity in passing to the transition state (37g). This result could be interpreted in terms of a rigid transition state leading to perepoxide formation, but the transition state for fragmentation might be equally rigid:

$$
\begin{array}{c}
BH \quad \delta^{\oplus} \\
\diagdown \\
O \text{-----} O \\
\end{array}
\quad
\begin{array}{c}
CH_3 \\
C \text{-----} C \diagup CH_3 \\
CH_3 \qquad CH_3 \qquad \qquad Br \quad \delta^{\ominus} \\
CH_3
\end{array}
$$
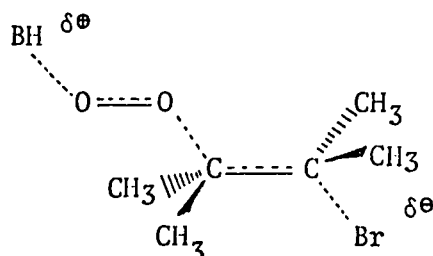
van de Sande (4) observed a transient absorption at τ 8.67 in the n.m.r. spectrum of a reacting mixture of bromohydroperoxide 18 and methanolic sodium methoxide. It seems quite unlikely that this absorption could be due to free 2,3-dimethyl-2-butene. The intermediate usually constituted 10% of the total solute species during the reaction (4) so that any associated oxygen would be evolved. The fact that the reaction gave a quantitative yield of allylic hydroperoxide (4) shows that no oxygen could have been lost. Furthermore, singlet oxygen would be rapidly deactivated by collision with solvent molecules (133,134,135). Consequently, if fragmentation did occur in the reaction, then the observed intermediate must have been formed from reaction between the olefin and singlet oxygen. This possibility is not unreasonable since the latter reaction proceeds at a diffusion controlled rate (126).

To test the possibility that a fragmentation reaction preceeded allylic hydroperoxide formation, it was decided to investigate a system in which fragmentation might occur, but in which the resulting olefin would be unreactive towards singlet oxygen. It is known that olefins lacking methyl group substituents are unreactive towards singlet oxygen (2) so that formation of such an olefin during the fragmentation reaction would be ideal. A suitable substrate which conforms to these requirements is erythro-2-bromo-1,2-diphenylethyl hydroperoxide (50). On reaction with base, 50 could fragment to yield trans-stilbene and singlet oxygen (125).

Preparation of erythro-2-Bromo-1,2-diphenylethyl Hydroperoxide (50):

A sample of crude 50 was obtained using a modification of the
general procedure for the preparation of bromohydroperoxides. A
solution of trans-stilbene in ether was added to a ten-fold excess of
98% hydrogen peroxide in ether at -40°. Then solid 1,3-dibromo-5,5-
dimethylhydantoin (2) was added to the mixture as a fine stream. After
warming to room temperature the mixture was washed with water when
large amounts of meso-stilbene dibromide separated (136). The filtered
ether solution was dried and evaporated to give crude 50, 7.9 g (75%
pure, 40% yield) as a solid. The n.m.r. spectrum (CDCl$_3$) of the crude
product showed absorption at τ 2.63 (singlet) and τ 4.67 (apparently a
doublet) with relative peak areas of 12.8:2; required 10:2. It is
likely that the major impurity in the product was trans-stilbene. The
identity of the crude 50 was established by reduction with acidified
potassium iodide to give erythro-2-bromo-1,2-diphenylethanol (51)
m.p. 83.5-84.2°; reported (137) m.p. 83.5-85.0°.

Reaction Between erythro-2-Bromo-1,2-diphenylethyl Hydroperoxide (50)
and Methanolic Sodium Methoxide:

A solution of 0.05 M 50 in methanol was allowed to react with four
equivalents of sodium methoxide at room temperature. The mixture was
stirred briefly and allowed to stand. No oxygen evolution was observed
during a period of three hours. After this time the solution which had
become yellow, was poured into water and extracted with ether. The
ether extract was concentrated and added to a solution of dianilinoethane
(26) in acetic acid (117). From this mixture benzaldehyde was recovered

as 1,2,3-triphenyltetrahydroimidazole in 17% yield (based on the hydroperoxide content of the starting material, [50]).

The aqueous layer was acidified with concentrated hydrochloric acid and extracted with 50 ml ether. Concentration of the ether extract gave only a trace of crystalline solid which was not examined further.

Luminescence from the Reaction Between erythro-2-Bromo-1,2-diphenylethyl Hydroperoxide (50) and Aqueous Sodium Hydroxide:

The isolation of benzaldehyde as a derivative from the reaction between 50 and base is in keeping with the formation of trans-3,4-diphenyl-1,2-dioxetane (52), eq. [78].

[78]

$$\text{50} \xrightarrow{\text{CH}_3\text{O}^{\ominus}} \text{52} \longrightarrow 2\ \text{C}_6\text{H}_5 - \text{CHO} .$$
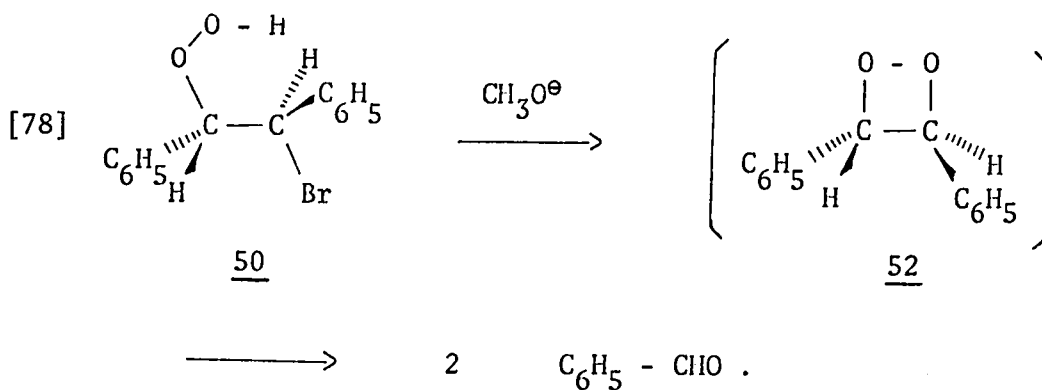
It seemed probable that under suitable conditions it might be possible to observe luminescence from the decomposition of 52.

A small quantity of benzene saturated with both the bromohydroperoxide, 50, and pyrene was shaken with a cold solution of aqueous 2 M sodium hydroxide and the mixture gradually heated. At 50° a green luminescence was observed from the benzene layer. The emission of light during this reaction adds strong support to the contention

that the reaction of 50 with base proceeds via the formation of trans-
3,4-diphenyl-1,2-dioxetane 52, eq. (78). Interestingly, all the
bromohydroperoxides described in Chapter I gave similar luminescence
under these conditions and also gave blue luminescence when heated
with aqueous base in the absence of pyrene.

The failure to obtain oxygen evolution from the reaction of 50
with base is in keeping with the earlier conclusion that, in the
reaction of bromohydroperoxides with base, 1,2-dioxetane formation is
energetically more favorable than fragmentation. Furthermore, since
1,2-dioxetanes are not involved in the formation of allylic
hydroperoxides from tetrasubstituted bromohydroperoxides, consideration
must be given to the proposal that perepoxides are the key intermediates
in this conversion.

It has been suggested that perepoxides are intermediates in the
sensitized photooxygenation of olefins (3,127). Foote and co-workers
(111) have studied the reaction of singlet oxygen with olefins in
sensitized photooxygenation reactions, with the object of detecting
the formation of perepoxides. They argue that product ratios should
not be influenced by electronic effects if the reaction is concerted.
Conversely, if the photooxygenation reaction involves the formation of
a perepoxide intermediate, then, with suitable substrates it should be
possible to use electronic effects as a probe to detect the formation
of the perepoxide. With the object of differentiating between these
alternative mechanisms, Foote and co-workers (111) studied the
sensitized photooxygenation of a series of trimethylstyrene
derivatives, eq. [79].

Measured ratio, 2.7 : 1.0
Statistical ratio, 1 : 2.0

The product distributions were measured from the photooxygenation of a variety of meta and para substituents ranging from the methoxyl to cyano groupings (111). Within experimental error, the product ratio was 2.7:1.0 for all the substituted trimethylstyrenes. The rate of photooxygenation was substantially increased by the presence of an electron-donating substituent showing that for stability, the transition state for reaction requires a high electron density. The requirement for high electron density and the failure to obtain a statistical ratio of products could be taken as evidence for a perepoxide intermediate in the photooxygenation reaction. However, the insensitivity of the product ratio to electronic effects militates against a mechanism involving a perepoxide intermediate (111).

Similar evidence comes from the photooxygenation of 2-methyl-2-butene (1) which yields equal amounts of both possible products, eq. [80] (111).

[80]

1   48 (48%)   12 (52%)

If a perepoxide intermediate had formed in this reaction, the formation of 48, would have been favored through the operation of statistical and electronic effects, eq. [81].

[81]

1

48
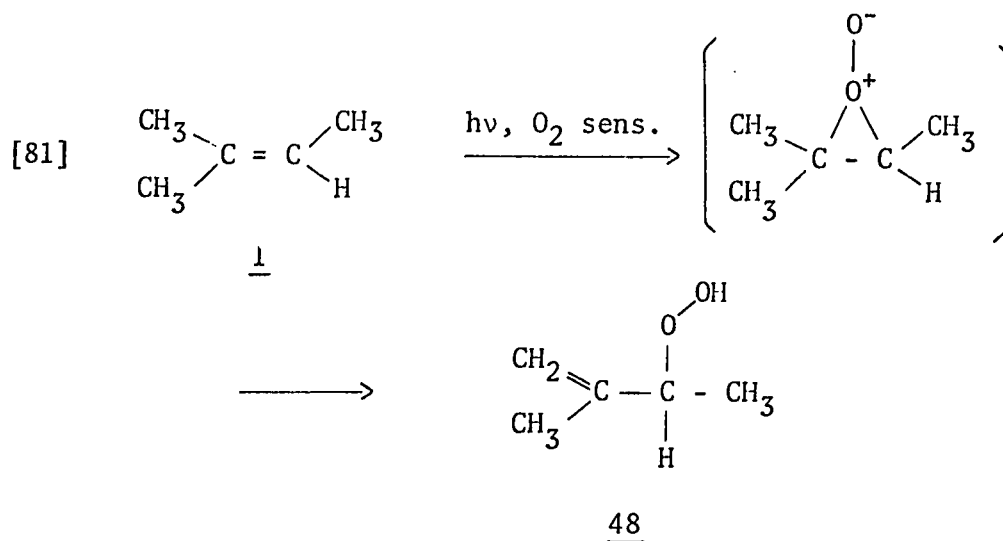
In order to gain further insight into the process whereby allylic hydroperoxides are formed from β-bromohydroperoxides it was decided to compare the product ratio from the photooxygenation of a trimethyl-styrene derivative with that obtained from reaction of the corresponding bromohydroperoxide with base. The substrate chosen for this investigation was 2-methyl-3-(4-methoxyphenyl)-2-butene (53).

Synthesis of 2-Methyl-3-(4-methoxyphenyl)-2-butene (53):

The olefin 53 was prepared using a synthetic sequence similar to that used by van de Sande (4) for the synthesis of deuterated olefins, eq. [82].
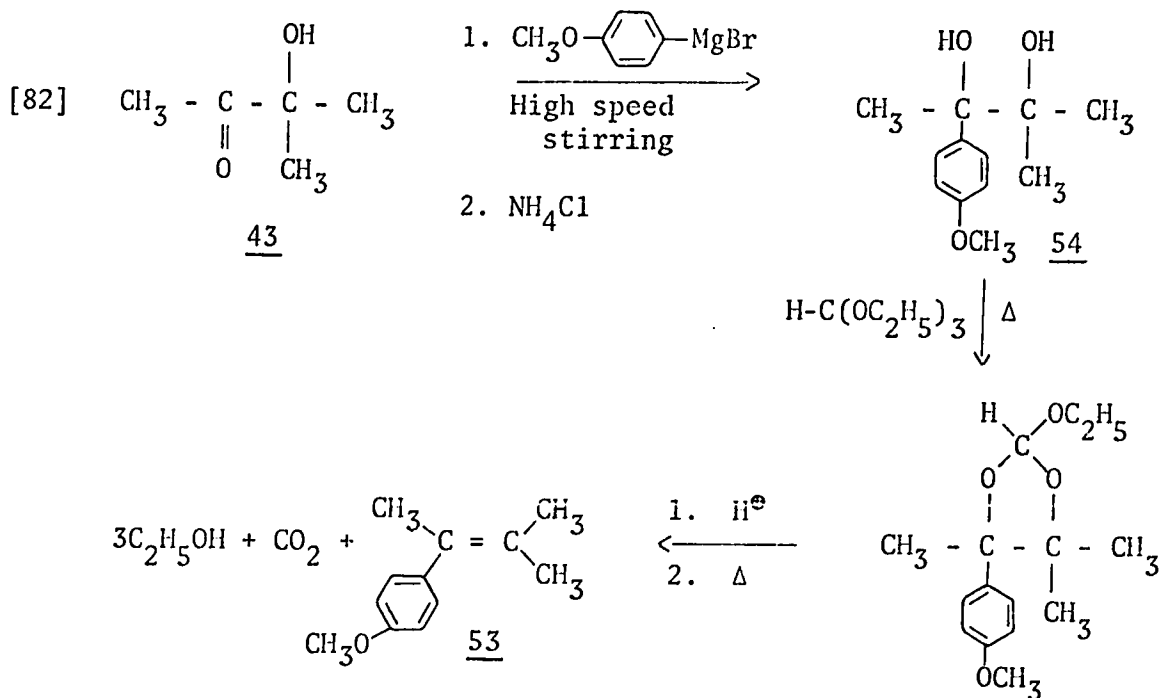
Reaction between dry 3-hydroxy-3-methyl-2-butanone (43) and 2.4 equivalents of the Grignard reagent derived from 4-bromoanisole, followed by hydrolysis with aqueous ammonium chloride and recrystallization of the crude product from carbon tetrachloride, gave 75% of 3-methyl-2(4-methoxyphenyl)-2,3-butanediol (54) (136).

The crude glycol, 54, was then heated in admixture with one equivalent of redistilled ethyl orthoformate (139). At 140°, only one equivalent of ethanol distilled from the mixture. The temperature was raised to 205° when a second equivalent of ethanol slowly distilled. Finally at 225° rapid distillation of ethanol commenced accompanied

by evolution of carbon dioxide. When gas evolution had ceased, 91%
of the expected three equivalents of ethanol had distilled from the
reaction mixture, eq. [83].

[83]
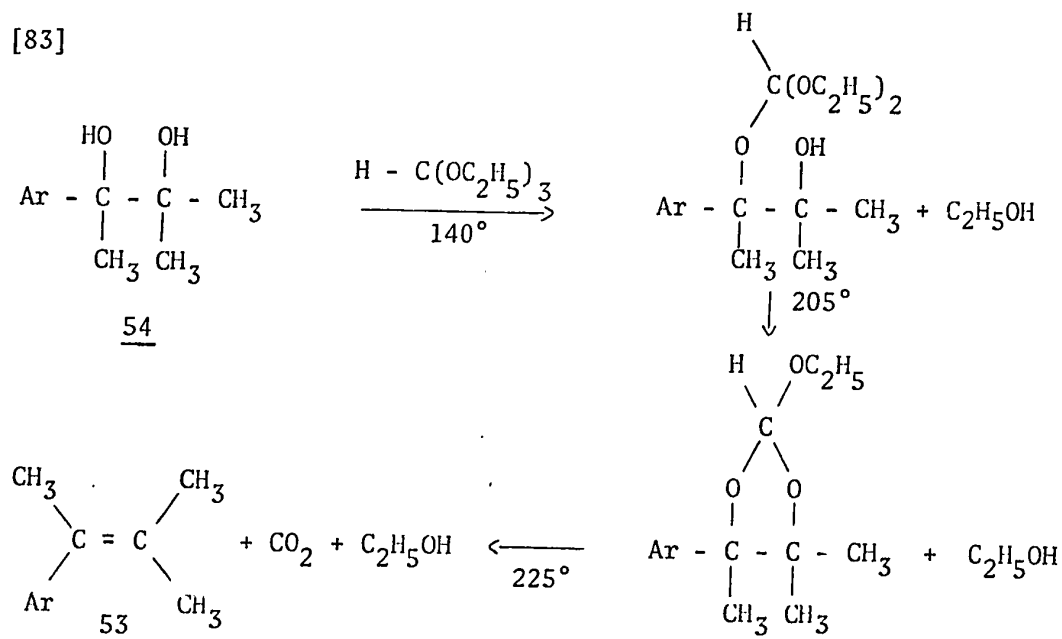
The residual oil was fractionally distilled to give 80% of
2-methyl-3-(4-methoxyphenyl)-2-butene (53). The colorless liquid
solidified on storing at 0° but melted again at room temperature. The
n.m.r. spectrum (CCl$_4$) showed absorption at τ 3.20 (quartet, J = 9.3
c.p.s.) due to the aromatic protons, τ 6.37 (singlet) due to the
protons of the methoxyl group, and τ 8.11, τ 8.23 and τ 8.43
(unresolved multiplets) due to the protons of the remaining three
methyl groups. The relative peak areas were 3.88;3.12;8.98; required
4:3:9.

Sensitized Photooxygenation of 2-Methyl-3-(4-methoxyphenyl)-2-butene

(53) in the Presence of Sodium Hydroxide:

A solution of 53 in 0.5 M methanolic sodium hydroxide was subected to Eosin-sensitized photooxygenation. Oxygen absorption ceased abruptly after 4 hours. An ether solution of the resulting products was reduced with lithium aluminum hydride to give 92% of a mixture of allylic alcohols, eq. [84].

[84]

$$
\begin{array}{c}
CH_3 \quad CH_3 \\
C = C \\
\end{array}
\qquad
\begin{array}{l}
1. \quad h\nu, \; O_2, \; sens. \\
\underline{\hspace{3cm}}\longrightarrow \\
2. \quad LiAlH_4
\end{array}
$$

CH_3O 53

$$
\begin{array}{ccc}
CH_2 \;\; OH & & HO \;\; CH_2 \\
C - C - CH_3 & + & CH_3 - C - C \\
\quad\;\; CH_3 & & \quad\;\; CH_3
\end{array}
$$

CH_3O

55   CH_3O 56
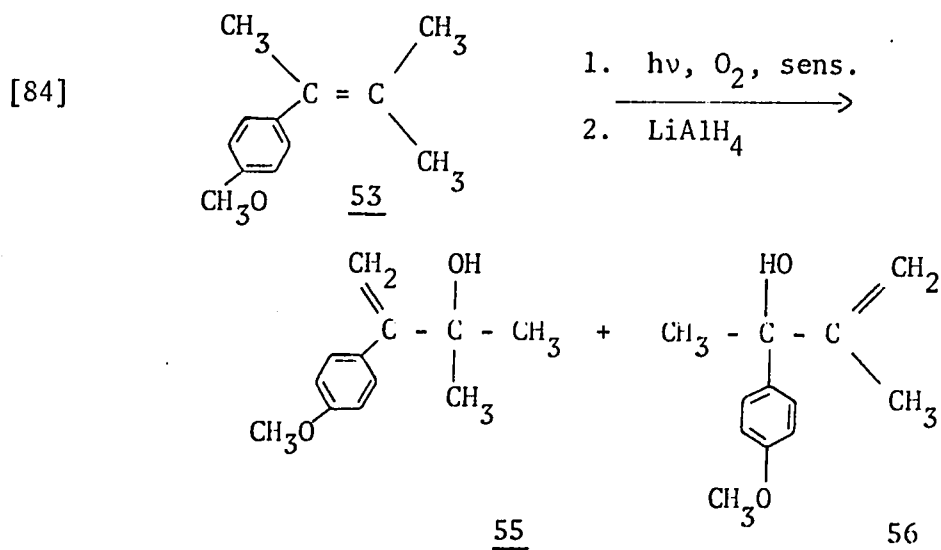
The n.m.r. spectrum (CCl_4) of the mixture showed a complex absorption at τ 2.60-3.42 due to the aromatic protons of both 55 and 56. In addition, the major product, 55, showed absorption at τ 4.70 and τ 5.13 (doublets) due to the vinyl protons, τ 6.27 (singlet) due to the methoxyl group protons, and τ 8.70 (singlet) due to the gem-dimethyl groups. The absorptions of the minor product, 56, partly coincided with those of the major product, 55. The minor product, 56, showed absorption at τ 4.90 (multiplet) and τ 5.13 (partly hidden multiplet) due to the vinyl protons, τ 6.27 (hidden singlet) due to the methoxyl

group protons, and τ 8.42 (unresolved multiplet) due to the allylic
methyl group. The absorption due to the benzylic methyl group of 56
was concealed either under the peak at τ 8.42 (due to 56), or under
the peak at τ 8.70 (due to 55). The ratio of the products 55:56, was
estimated by integration of the peaks at τ 4.70 (due to 55) and τ 4.90
(due to 56). From the average of three integrations the ratio of 55
to 56 was found to be 2.5:1.0, in agreement with the value quoted by
Foote (111) for a series of substituted trimethylstyrenes photo-
oxygenated in the absence of base. This experiment shows that base has
no effect on the sensitized photooxygenation reaction in keeping with
Foote's conclusion (111) that the reaction is concerted.

Preparation of 2-Bromo-2-methyl-3-(4-methoxyphenyl)-3-butyl

Hydroperoxide (57):

An ether solution of 57 was prepared using a modification of the
general procedure described in Chapter I for the preparation of
β-bromohydroperoxides, eq. [85].

[85]
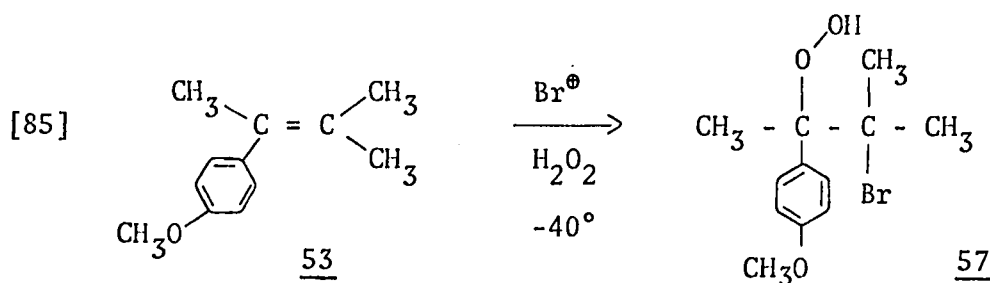
A solution of 53 in ether was added to a ten-fold excess of
hydrogen peroxide in ether at -40°. The resulting mixture was then
treated with 1,3-dibromo-5,5-dimethylhydantoin (2) and allowed to
warm to room temperature. The resulting ether solution was washed

with water and dried. Any attempt to remove the ether resulted in gradual blackening of the product so the ether solution was used immediately in the following experiments. Iodometric titration of an aliquot of the solution showed that 73% of 57 had been formed in the reaction. A second aliquot was repeatedly evaporated with added carbon tetrachloride. The n.m.r. spectrum (CCl_4) of the resulting solution showed a complex absorption at τ 2.32-3.33 due to the protons of the phenyl ring, τ 6.23 (singlet) due to the methoxyl group protons, τ 8.11 (singlet) due to the benzylic methyl group and τ 8.28 and 8.33 (singlets) due to the protons of the non-equivalent gem-dimethyl groups of 57. In addition relatively small absorptions occurred at τ 7.52, τ 7.90 and τ 8.20-8.50.

The remaining ether solution of 57 was allowed to react, at 0°, with 0.5 M sodium hydroxide in methanol for 30 minutes. The resulting solution was diluted with water, neutralized with acetic acid and extracted with ether. The dried ether extract was reduced with lithium aluminum hydride to give an impure mixture of allylic alcohols. The impure mixture was chromatographed on basic alumina to give 33% of the starting olefin, 53, and 57% of a mixture of pure allylic alcohols. The material balance throughout the entire sequence of operations was 90%. The n.m.r. spectrum (CCl_4) of the mixture of alcohols showed a fairly clean A_2B_2 pattern centred at τ 3.03, due to the aromatic protons of both 55 and 56. In addition, the major product, 55, showed absorption at τ 4.67 and τ 5.12 (doublets) due to the vinyl protons, τ 6.26 (singlet) due to the methoxyl group protons, τ 8.08 (broad singlet) due to the hydroxyl group proton and τ 8.68 (singlet) due to

the gem-dimethyl groups. The absorptions of the minor product, 56, were difficult to detect. At high spectrum amplification, a small peak at τ 4.89 (multiplet) was seen, due to a vinyl proton, together with a small peak at τ 8.42 due to the allylic methyl group. Integration of the olefinic region of the spectrum revealed a hidden peak, due to the other vinyl proton of 56, at τ 5.12. The absorption of the benzylic methyl group of 56 was concealed either under the peak at τ 8.42 (due to 56) or under the peak at τ 8.68 (due to 55). The ratio of 55:56 was estimated from the integrations of the peak at τ 4.67 (due to 55) and the peak at τ 4.89 (due to 56). From the average of three integrations the ratio of 55:56 was found to be ca. 6.3:1. The result is summarized in equation [86].
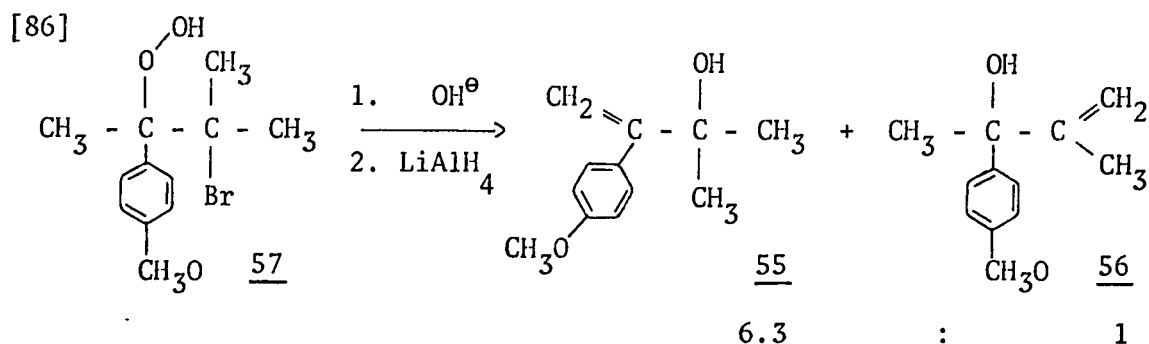
This result shows immediately, that during the reaction of 57 with base, the hydroperoxy group is transferred from the benzylic carbon to the homobenzylic position. Furthermore, assuming that the product ratio was unaffected during work-up, then it appears that the product ratio from the reaction of the bromohydroperoxide 57 with base was different from that observed during the photooxygenation of the olefin 53. However, it is difficult to place firm reliance on these ratios since

the product balance in the two reactions was only 90%. Consequently, from this experiment alone, it is not possible to decide whether the allylic hydroperoxides from the two types of reaction are formed <u>via</u> the same, or different intermediates. However, a high yield of allylic hydroperoxide from the base-promoted reaction of the bromo-hydroperoxide 58 would be surprising if a fragmentation reaction were involved, because the resulting olefin 53 is not very reactive towards singlet oxygen. The photooxygenation of 53 takes 4 hours to complete under conditions where the photooxygenation of an equivalent amount of tetramethylethylene is complete in 45 minutes (4).

From the results of van de Sande (4), it is possible to make a further comparison between the photooxygenation reaction and the base-promoted reaction of tetrasubstituted β-halohydroperoxides. Firstly, both reactions give allylic hydroperoxides. Secondly, both reactions give essentially the same product ratios. For example, photooxygenation of 1,2-dimethylcyclohexene produces the allylic hydroperoxides, 58 and 59, in relative yields of 89% and 11%, respectively, eq. [87] (111).

[87]

58 (89%)   59 (11%)
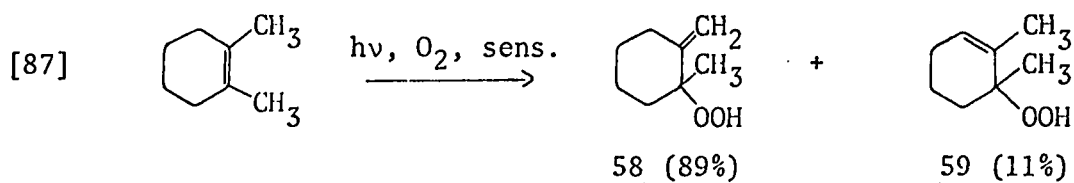
Similarly, the base-promoted reaction of 2-bromo-1,2-dimethylcyclohexyl hydroperoxide (60) gives the products 58 and 59 in a ratio of ca. 97:3(4), eq. [88].

[88]   Br

         ''''CH₃
         CH₃   OH⊖
         ''''OOH   ─────→   CH₂   CH₃
                      0°   ‖   ‖
                                 CH₃   CH₃
                                 OOH   OOH

         60   58 (97%)   59 (3%)
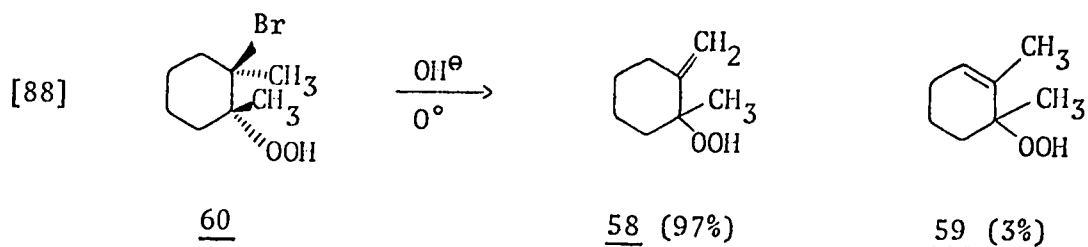
Clearly, very precise experimentation would be required to establish any real difference between the reactions of equations [87] and [88]. Finally, the reactions may be compared on the basis of the isotope effects observed when a deuterated olefin is subjected to both sequences. Photooxygenation of 2,3-bis-trideuteriomethyl-2-butene (61) gave a mixture of two allylic hydroperoxides, eq. [89] (4).

[89]   CD₃   CD₃   hv, O₂, sens.
            \C = C/   ──────────────→
     CH₃/   \CH₃
            61

                        CD₃
                         |
         CD₃   CH₃   CD₃
            \C — C — OOH   +   \C — C — OOH
     CH₂// | CD₂//   \CH₃
            CH₃
            62   63
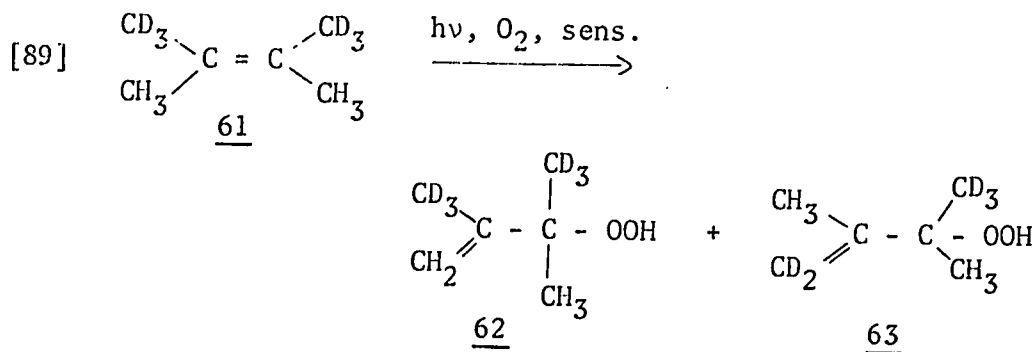
From the ratio of the products 62 and 63, the isotope effect k_H/k_D was found to be 1.35 ± 0.07 for a variety of sensitizers (4). Conversion of the deuterated olefin, 61, to the corresponding bromohydroperoxide followed by reaction with base gave a different ratio of the products 62 and 63. From this ratio an isotope effect of 2.12 ± 0.1 was found (4). The dissimilar isotope effects observed in these reactions indicates that a different mechanism operates in each case.

In conclusion, it can be seen that the evidence given in this

chapter shows that 1,2-dioxetanes are not involved in the formation of allylic hydroperoxides from tetrasubstituted β-halohydroperoxides, but as yet no clear decision can be made about the nature of the true intermediate involved in this process.

EXPERIMENTAL

Isolation of 3,3,4,4-Tetramethyl-1,2-dioxetane (49):

Several methods were explored for the synthesis of 49, all

involving the reaction between 3-bromo-2,3-dimethyl-2-butyl

hydroperoxide (18) (4) and silver acetate. Benzene solutions

containing 49 were prepared by one of the following methods:

(a) Aqueous Silver Acetate.

A solution of the bromohydroperoxide 18 (2.065 g, 95.4% pure,

0.01 mole) (4) in 10 ml benzene was shaken in the dark with powdered

silver acetate (3.34 g, 0.02 mole) which was partly dissolved in

170 ml water. The mixture was shaken at room temperature for 15

minutes. The resulting mixture was filtered with suction. The yellow

precipitate of silver bromide was washed with 10 ml benzene. The

filtrate and washings were combined and the organic layer separated.

The dried organic layer contained the 1,2-dioxetane 49 together with

a number of other materials.

(b) Silver acetate in Benzene.

A solution of the bromohydroperoxide 18 (3.088 g, 95.7% pure,

0.015 mole) in 30 ml of benzene, was shaken in the dark at room

temperature with powdered silver acetate (2.755 g, 0.0165 mole). After

30 minutes the mixture was filtered with suction. The precipitate of

silver bromide was washed with 5 ml benzene, and the filtrate and

washings combined.

(c) Crystalline Silver Acetate in Benzene.

Silver acetate powder was dissolved in hot water containing a
few drops of glacial acetic acid. The resulting solution was filtered
through two layers of fluted filter paper and then allowed to cool.
The crystals which formed were collected and dried in a vacuum oven at
40°. These crystals were used to prepare a benzene solution of the
1,2-dioxetane 49 as described in (b) above, except that at least two
hours shaking were required for complete reaction. Unfortunately, the
completeness of reaction could only be judged by examination of the
n.m.r. spectrum of the filtered solution.

Work-up Procedure.

The solutions (a), (b) and (c), prepared as directed above, were
examined using n.m.r. spectroscopy. Solutions (a) and (b) contained
2,3-dimethyl-3-hydroperoxy-1-butene (19) and the 1,2-dioxetane, 49,
in approximately 2:1 ratio. This ratio was improved to 1.5:1 in the
solution derived by method (c). These ratios were judged from the
peak heights of the twelve proton peak of 49, at τ 8.83, and the six
proton peak due to the gem-dimethyl group of 19 at τ 8.76. Solutions
(b) and (c) also contained acetic acid and perhaps acetone which both
give signals at τ 8.39 in benzene. The acetic acid could be removed
from solutions (b) and (c) by washing with 20 ml of water. In
addition to the above materials the n.m.r. spectra of solutions (a),
(b) and (c), showed absorption due to an unidentified neutral material
at τ 9.15. This substance was difficult to remove from the mixture and
since solutions (b) and (c) contained the least quantity of this
unknown material the latter methods are the preferred procedures.

The reaction time for method (c) was highly variable and different batches of silver acetate crystals gave reaction times of 2-4 hours.

After removing acetic acid, solution (b) above was shaken six times with 20 ml of 2 M aqueous sodium hydroxide. The aqueous extract contained only the allylic hydroperoxide 19. The yield of recovered 19, 30%, was estimated iodometrically (30). The organic layer was finally washed with 20 ml water and dried over molecular sieves (4A). The solution was then evaporated, in the manner described for the preparation of 3,3,4-trimethyl-1,2-dioxetane (20) (Chapter II). A mixture of liquid and crystals was obtained. The moist crystals were recrystallized from 4 ml pentane, then again from 3 ml pentane at -20° using a microfiltration apparatus. Finally, the yellow crystals were sublimed at 0.5 mm to yield rectangular yellow platelets of 49, m.p. 76-77° (sealed tube). The melting point apparatus had to be pre-heated to 70° to avoid sublimation of the peroxide. The molten 49 emitted a faint blue light. The yield of 49 was ca. 3-6%. The peroxide was very volatile, often subliming to another part of the sample tube even when stored at 0°. The crystals of 49 rapidly liberated iodine on treatment with potassium iodide in aqueous acetic acid.

The n.m.r. spectrum of the peroxide showed a singlet absorption at τ 8.83 (benzene) and τ 8.58 (CCl_4). The n.m.r. spectrum of 49 in fluorotrichloromethane was recorded at -40°, -70° and -90°. All the spectra ($CFCl_3$) showed singlet absorption at τ 8.55 with a peak-width at half height of 1.9 c.p.s.

The infrared spectrum of the peroxide (CCl_4) has been described

in the results and discussion section.

The Molecular Weight of 3,3,4,4-Tetramethyl-1,2-dioxetane (49):

(a)   Mass Spectrum of 3,3,4-Tetramethyl-1,2-dioxetane (49).

The mass spectrum of 49 was obtained using an A.E.I. MS-12 mass spectrometer with a water cooled source and direct insertion of the sample. The ionization potential was maintained at 70 volts. Peaks were observed at m/e 116.84, 69, 58 and 43. The parent peak at m/e 116, corresponds to a molecular formula of $C_6H_{12}O_2$.

(b)   Osmometry.

An attempt was made to determine the molecular weight of 49 using a Mechrolab Vapour Pressure Osmometer, Model 301 A with benzene as solvent. Although the temperature of the apparatus was only 32.5°, rapid decomposition of 49 occurred as revealed by a continuous drift in the meter readings. Consequently, this method was discontinued.

(c)   Freezing Point Depression.

The molecular weight of 49 was readily determined using an all-glass apparatus commonly used in undergraduate laboratories (131). Shawinigan, reagent grade benzene was used for the determination. Each freezing point was determined three times. Pure benzene (12.27 g) froze at thermometer readings of 0.713°, 0.712° and 0.712°. Addition of 0.1012 g of napthalene gave a solution which froze at thermometer readings of 0.371°, 0.370° and 0.369°. From the mean freezing point depression, 0.342°, the cryoscopic constant for benzene was found to be 5313 (131). Using a fresh sample of benzene (12.50 g) the freezing point occurred at thermometer readings of 0.710°, 0.710° and 0.710°.

Addition of 0.0878 g of pure 49 gave a solution which froze at 0.378°,

0.378° and 0.378°. From the freezing depression, 0.332°, the

molecular weight of 49 was found to be 112.4; required 116.16 for

$C_6H_{12}O_2$.

Thermal Decomposition of 3,3,4,4-Tetramethyl-1,2-dioxetane (49):

A solution of 49 in benzene was subjected to g.l.c. analysis on

a 5 ft. x 1/4 in. column of 10% carbowax 1500 on Chromosorb W at 65°.

Only one product peak was observed with retention time identical to

that of acetone. The yield of acetone from the decomposition of 49

was measured by decomposing 49 as a solution in benzene containing

anisole as internal standard. The mixture was contained in a sealed

n.m.r. tube. By comparing the average of six integrations of the

n.m.r. absorptions due to the methoxyl group of anisole (τ 6.68) and

49 (τ 8.83), before heating at 70° overnight, with that of anisole

and acetone (τ 8.39) after heating, the yield of acetone was estimated

to be 96 ± 6%.

Luminescence in the Thermal Decomposition of 3,3,4,4-Tetramethyl-1,

2-dioxetane (49):

A faint bluish-white luminescence was observed when a small volume

of 0.1 M 49 in benzene was heated to 70°. Brighter, green luminescence

was observed, when a similar solution of 49 containing pyrene was heated

to 70°. The luminescence spectrum of the light emitted during the

decomposition of 49 has not been recorded.

Lack of Reaction Between 3,3,4,4-Tetramethyl-1,2-dioxetane (49) and

Methanolic Sodium Methoxide:

A sample of solid 49 (0.0063 g, 5.43 x 10^{-5} mole) was added to

0.5 ml of 0.11 M methanolic sodium methoxide at room temperature. The

resulting solution was transferred to an n.m.r. tube which was then

inserted into the probe of an n.m.r. spectrometer with the probe

temperature at 35°. After 90 minutes, the only solute absorptions

visible were at τ 7.81, due to acetone, and τ 8.51 due to the unreacted

starting material. There were no absorptions which could be attributed

to 2,3-dimethyl-3-hydroperoxy-1-butene (19) or pinacol. From the

integration of the peak due to acetone and the peak due to 49, the

extent of decomposition of 49 was judged to be ca. 27%.

erythro-2-Bromo-1,2-diphenylethyl Hydroperoxide (50):

A solution of trans-stilbene (9.0 g, 0.05 mole) in 250 ml ether

was added to a solution of 98% hydrogen peroxide (17 g, 0.5 mole) in

50 ml ether at -40°. Solid 1,3-dibromo-5,5-dimethylhydantoin (2)

(7.15 g, 0.025 mole) was then added as a fine stream. The reaction

mixture rapidly acquired a strong brown coloration. The mixture and

cooling bath were allowed to warm to room temperature. The mixture

was then washed four times with 50 ml water when copious amounts of

white crystals began to form. The formation of the crystals was

accompanied by loss of the brown coloration. The solid was removed

by filtration and recrystallized from benzene. The recrystallized

material was identified as meso-stilbene dibromide, m.p. 234-236°;

reported (136) m.p. 236°.

The washed ether layer was dried and concentrated to ca.50 ml

when more meso-stilbene dibromide separated. The concentrated ether

solution was filtered and the filtrate evaporated to give solid 50,

7.9 g, 75% pure by iodometric titration (30). The yield of 50 was

40% of theory. The n.m.r. spectrum has been described in the results

and discussion section.

erythro-2-Bromo-1,2-diphenylethanol (51) from 50:

A solution of 50 (0.91 g, 75% pure, 2.33 x 10^{-3} mole) in 8 ml of

chloroform, was allowed to react with 2 g of potassium iodide in a

mixture of 12 ml glacial acetic acid and 2 ml water at 25°. After 15

minutes the liberated iodine was destroyed by adding excess aqueous

sodium thiosulfate. The resulting mixture was extracted with 25 ml of

ether. The dried ether extract was filtered to give crude 51. The

crude product was recrystallized three times from hot heptane to give

pure 51, m.p. 83.5-84.2°; reported (137) m.p. 83.5-85°. The n.m.r.

spectrum ($CDCl_3$) showed absorption at τ 2.70 (singlet) due to the

protons of the phenyl ring, τ 4.88 (apparently a doublet) due to the

two methine protons and τ 7.62 (singlet) due to the hydroxyl group

proton with relative peak intensities of 10.11:1.94:0.94; required

10:2:1.

Reaction Between erythro-2-Bromo-1,2-diphenylethyl Hydroperoxide (50)

and Methanolic Sodium Methoxide:

To 50 ml of 0.05 M 50 in methanol was added 20 ml of 0.5 M sodium

methoxide in methanol at room temperature. The solution rapidly

became yellow, but no gas evolution occurred. After 3 hours the

mixture was poured into 150 ml of water and extracted with 50 ml ether. The ether extract was washed once with 50 ml water and dried. Then 20 ml of glacial acetic acid was added together with solid dianilino-ethane (26) (1.06 g, 0.005 mole). The resulting mixture was concentrated to 50 ml when 0.26 g of 1,2,3-triphenyltetrahydroimidazole separated, m.p. 135-136° and mixture melting point with authentic (26) 1,2,3-triphenyltetrahydroimidazole 135-136°. The yield of benzaldehyde, as 1,2,3-triphenyltetrahydroimidazole, was 17% of theory.

The aqueous layer from the above reaction was acidified with hydrochloric acid and extracted with 50 ml ether. The dried ether extract was evaporated to give a trace of crystalline material which was not examined further.

Luminescence from the Reaction Between erythro-2-Bromo-1,2-diphenylethyl Hydroperoxide (50) and Aqueous Sodium Hydroxide:

A solution of 2 ml benzene saturated with 50 and pyrene was added to 2 ml 2 M aqueous sodium hydroxide. The resulting mixture was heated to 50° when a faint green luminescence was observed in the organic layer. Similar luminescence was observed when the same experiment was carried out using trans-2-bromo-cyclohexyl hydroperoxide (3), 2-bromo-1-phenylethyl hydroperoxide (16) or 3-bromo-2-methyl-2-butyl hydroperoxide (11). The latter materials also gave blue luminescence when heated with aqueous sodium hydroxide in the absence of pyrene.

2-Methyl-3-(4-methoxyphenyl)-2-butene (53):

A solution of 3-hydroxy-3-methyl-2-butanone (43) (43 g, 0.5 mole) in 100 ml ether was added dropwise to 1.2 moles of a Grignard reagent,

prepared from 4-bromoanisole (225 g, 1.2 mole), and magnesium metal (29.7 g, 1.22 moles), in 750 ml ether. The mixture was agitated by means of a high-speed stirrer. Towards the end of the addition a glutinous mass separated from the mixture which could not be agitated. As the addition continued more of this material was deposited. The mixture was heated under reflux for a further 30 minutes at the end of the addition. The mixture was then hydrolyzed by adding 1.2 moles of ammonium chloride as a 25% aqueous solution. It was necessary to manually scrape the glutinous deposit off the sides of the flask during the hydrolysis. The ether layer was separated by decantation and the residual slurry washed several times with ether. The combined ether extracts were dried by slowly passing the solution through a column of molecular sieves (4A). The dried ether solution was concentrated by distillation through a 15 cm vigreaux column. The pressure was then reduced to 7 mm when 40 g of anisole were recovered, b.p. 33°. The hot residue, at 75°, was added to 100 ml of hot heptane and swirled when the oily product rapidly solidified. The crude product was recrystallized from 100 ml of hot carbon tetrachloride to give 79 g (75%) of 3-methyl-2-(4-methoxyphenyl)-2,3-butandiol (54) m.p. 76-84°; reported (138) m.p. 87-88°. A small quantity of the glycol, 54, was further recrystallized from hot carbon tetrachloride to give material melting at 82-85°.

For the next stage in the synthesis, a mixture of 54 (70.0 g, 0.333 mole) was heated at 140° in a conventional distillation apparatus (139). Within two hours 14.4 g (0.313 mole) of ethanol had distilled over. The temperature of the heating bath was raised to 205°. After

a further 12 hours 24.6 g (0.535 mole) of ethanol had distilled. The

heating bath was again raised to 225° when ethanol distillation resumed,

together with evolution of carbon dioxide (lime water test). After one

hour at 225°, 41.7 g (0.907 mole) of ethanol had been recovered and

gas evolution had ceased. The residual oil was distilled to give

47.3 g (80%) of 2-methyl-3-(4-methoxyphenyl)-2-butene (53), b.p.

239-243° (702 mm), n_{26}^D = 1.5309; reported (140) b.p. 234° (760 mm),

n_D^{25} = 1.5295. The n.m.r. spectrum (CCl_4), described in the results

and discussion section, agrees with the published spectrum (140).

Sensitized Photooxygenation of 2-Methyl-3-(4-methoxyphenyl)-2-

butene (53) in the Presence of Sodium Hydroxide:

A solution of 53 (2.095 g, 11.9 mmole) in 30 ml of 0.5 M methanolic

sodium hydroxide was subjected to Eosin-sensitized photooxygenation

(4). After 4 hours, oxygen uptake ceased abruptly. The mixture was

poured into 100 ml water and neutralized with glacial acetic acid.

The resulting mixture was extracted twice with 50 ml ether. The

combined ether extracts were washed once with 50 ml of saturated

aqueous sodium chloride solution and dried. The dried ether extract

was then added to a slurry of 1.0 g of lithium aluminum hydride in

15 ml ether and the resulting mixture heated under reflux for one hour.

After this time 15% aqueous potassium hydroxide was added until the

organic layer became clear. The organic layer was removed by

decantation, leaving a slurry which was washed several times with

ether. The combined ether extracts were dried and evaporated to

constant weight. There was obtained, 2.103 g (92%) of a mixture of

allylic alcohols. The n.m.r. spectrum, described in the results and
discussion section, showed the presence of 3-hydroxy-3-methyl-2-(4-
methoxyphenyl)-1-butene (55) and 3-hydroxy-2-methyl-3-(4-methoxyphenyl)-
1-butene (56) in a ratio of 2.5:1.

2-Bromo-2-methyl-3-(4-methoxyphenyl)-3-butyl Hydroperoxide (57):

A solution of the olefin 53 (8.8 g, 0.05 mole) in 25 ml ether was
added to a mixture of 98% hydrogen peroxide (17 g, 0.5 mole) and 50
ml ether at -40°. Then solid 1,3-dibromo-5,5-dimethylhydantoin (2)
(7.15 g, 0.025 mole) was added as a fine stream. The mixture and
cooling bath were allowed to warm to room temperature. The resulting
solution was washed six times with 50 ml water and the organic layer
separated. Any attempt to remove the solvent from the dried ether
solution of 57 resulted in loss of the peroxide content and blackening
of the product. Consequently, the ether solution of 57 was made up to
100 ml with ether and used immediately. A 10 ml aliquot of this
solution was titrated for peroxide content (30). This estimation
showed that 73% of 57 had been formed in the reaction. A further 10
ml of the ether solution was diluted with 10 ml carbon tetrachloride
and evaporated to ca. 5 ml volume. The n.m.r. spectrum of the resulting
ether-free solution has been described in the results and discussion
section.

The remaining 80 ml of ether solution were immediately cooled to
0° and 100 ml of 0.5 M methanolic sodium hydroxide added over a period
of 15 minutes. After a further 30 minutes at 0° the mixture was diluted
with 100 ml water and neutralized with glacial acetic acid. The

resulting mixture was extracted twice with 100 ml of ether. The combined ether extracts were washed with 100 ml of saturated aqueous sodium chloride, dried, and concentrated to 100 ml volume. One quarter of this solution was diluted with 10 ml carbon tetrachloride and evaporated to 5 ml volume. The n.m.r. spectrum (CCl_4) of this solution showed the presence of several compounds. The major components were provisionally judged to be the starting olefin 53 and 3-hydroperoxy-3-methyl-2-(4-methoxyphenyl)-1-butene.

The remaining 75 ml of the allylic hydroperoxide solution was added to a stirred slurry of lithium aluminum hydride (2.5 g) in 60 ml ether. The resulting mixture was heated under reflux for one hour, then 15% aqueous potassium hydroxide was added until the organic layer became clear. The ether layer was decanted and the residual slurry washed several times with ether. The combined ether extracts were dried and evaporated to constant weight. Eighty-five percent of the residual oil was chromatographed on 300 g of basic alumina using pentane as eluent. The first material to be eluted was the starting olefin 53. When elution of the olefin 53 had ceased, the pentane solution was evaporated to constant weight. There was obtained 1.48 g of the starting olefin 53, (33%) based on the amount of olefin used initially. This material gave a single peak on g.l.c. analysis using a 5 ft. x 1/4 in. column of Q.F. 1 at 140°. The olefin was identified by comparison of its g.l.c. retention time with that of authentic 2-methyl-3-(4-methoxyphenyl)-2-butene (53).

The column of alumina was further eluted with 50:50 v/v pentane-ether to give a minute amount of a crystalline solid which was not

examined further. Finally, the column was eluted with ether until the eluent was solute free. The resulting ether solution was evaporated to constant weight when 2.80 g of a mixture of allylic alcohols was obtained, (57% based on the amount of olefin used initially). The n.m.r. spectrum of this mixture, described in the results and discussion section, showed the presence of 3-hydroxy-3-methyl-2-(4-methoxyphenyl)-1-butene (55) and 3-hydroxy-2-methyl-3-(4-methoxyphenyl)-1-butene (56) in a ratio of ca. 6.3:1.

BIBLIOGRAPHY

1. G. O. Schenck, Angew. Chem., 69, 579 (1957).

2. K. Gollnick and G. O. Schenck, Rev. Pure Appl. Chem., 9, 507 (1964).

3. K. R. Kopecky and H. J. Reich, Can. J. Chem., 43, 2265 (1965).

4. J. H. van de Sande, Ph.D. Thesis, University of Alberta, 1968.

5. A. Roedig, in Houben Weyl "Methoden der Organischen Chemie", Vol. 5/4, E. Muller, Ed., George Thieme Verlag, Stuttgart, 1960, p. 139.

6. R. Strah, in Houben Weyl, "Methoden der Organischen Chemie", Vol. V/3, E. Muller, Ed., George Thieme Verlag, Stuttgart, 1962, p. 768.

7. E. R. Bell, R. H. Dickey, J. H. Riley, F. F. Rust, and W. B. Vaughn, Ind. Eng. Chem., 41, 2597 (1949).

8. A. Rieche, E. Schmitz, and M. Schulz, Z. Chem., 3, 433 (1963).

9. K. Weissermel and M. Lederer, Chem. Ber., 99, 3244 (1966).

10. S. Winstein, E. Grunwald, R. E. Buckles, and C. Hanson, J. Am. Chem. Soc., 70, 816 (1948).

11. P. A. Sutton, Chem. and Ind., 272 (1951).

12. Org. Syn. Coll. Vol. I, 185 (1941).

13. D. M. Rosie and R. L. Grob, Anal. Chem., 29, 1263 (1957).

14. S. Winstein, J. Am. Chem. Soc., 64, 2792 (1942).

15. Kindly donated by Mr. S. Evani.

16. N. Kornblum and H. E. de la Mare, J. Am. Chem. Soc., 73, 880 (1951).

17. S. S. Medwedew and E. Alexejewa, Chem. Ber., 65, 133 (1932).

18. C. C. J. Culvenor, W. Davies, and N. S. Heath, J. Chem. Soc., 278 (1949).

19. H. J. Dauben, Jr. and L. L. McCoy, J. Am. Chem. Soc., 81, 4863 (1959).

20. Org. Syn. Coll. Vol. II, 5 (1943).

21. M. Schulz, A. Rieche, and K. Kirschke, Chem. Ber., _100_, 370 (1967).

22. A. Rieche, M. Schulz, and K. Kirschke, Chem. Ber., _99_, 3244 (1966).

23. J. Read and W. G. Reid, J. Chem. Soc., 1487 (1928).

24. R. E. Buckles and J. E. Maurer, J. Org. Chem., _18_, 1585 (1953).

25. C. O. Guss and R. Rosenthal, J. Am. Chem. Soc., _77_, 2549 (1955).

26. H. W. Wanzlick and W. Sochel, Chem. Ber., _86_, 1463 (1963).

27. W. H. Richardson, J. W. Peters, and W. P. Konopka, Tetrahedron Letters, No. _45_, 5531 (1966).

28. L. Dulog and W. Voght, Tetrahedron Letters, No. _42_, 5169 (1966).

29. The Ring Index, McGregor and Werner, Inc., 1960, p. 4.

30. Org. Syn., _34_, 92 (1954).

31. Y. Shimodoi, M. Sashio, and N. Murata, Kogyo Kagaku Zasshi, _63_, 2143 (1960).

32. M. F. Clarke and L. N. Owen, J. Chem. Soc., 315 (1949).

33. Org. Syn. Coll. Vol. II, 171 (1943).

34. R. Criegee, Ann., _481_, 263 (1931).

35. W. A. Patterson, Anal. Chem., _26_, 824 (1954).

36. B. W. Christensen and A. Kjaer, Proc. Chem. Soc., 307 (1962).

37. A. A. Frost and R. G. Pearson, in "Kinetics and Mechanism", Second Edition, John Wiley and Sons, Inc., New York·London, 1961, (a) p. 17, (b) p. 19, (c) p. 13, (d) p. 14, (e) p. 23, (f) p. 101, (g) p. 111.

38. J. F. Bunnett, in "Technique of Organic Chemistry", Vol. VIII, 1961, p. 199.

39. F. McCapra, Chem. Commun., 155 (1968).

40. R. Livingston and W. R. Ware, J. Chem. Phys., _39_, 2539 (1963).

41. H. Nilsson and L. Smith, Z. Physik Chem., _A166_, 136 (1933).

42. E. G. V. Percival, Q. Revs., _3_, 373 (1949).

43. F. D. Mango and J. H. Schachtschneider, J. Am. Chem. Soc., 89, 2484 (1967).

44. H. Hogeveen and H. C. Volger, J. Am. Chem. Soc., 89, 2486 (1967).

45. K. B. Wiberg and B. J. Nist, J. Am. Chem. Soc., 83, 1226 (1961).

46. Varian Catalogue, Volume 1, spectrum 33.

47. G. van Dyke Tiers, "Characteristic Nuclear Magnetic Resonance Shielding Values for Hydrogen in Organic Structures", Central Research Department, Minnesota Mining and Manufacturing Company, St. Paul, Minnesota, 1958.

48. S. W. Benson, J. Chem. Phys., 40, 1007 (1964).

49. R. H. Hunt, R. A. Leacock, C. W. Peters and K. T. Hecht, J. Chem. Phys., 42, 1931 (1965).

50. R. Hoffmann and R. B. Woodward, J. Am. Chem. Soc., 87, 2046 (1965).

51. R. B. Woodward, in "Aromaticity", Chem. Soc. Special Publ., No. 21, 1967, p. 217.

52. R. Hoffmann, Abstracts of the 21st National Organic Chemistry Symposium of the American Chemical Society, June 15-19, 1969, in Salt Lake City, Utah, p. 109.

53. S. W. Benson in "Thermochemical Kinetics", John Wiley and Sons, Inc., New York, London, Sydney, 1968.

54. R. F. Borkman and D. R. Kearns, J. Chem. Phys., 44, 945 (1966).

55. E. E. Barnes and W. T. Simpson, J. Chem. Phys., 39, 670 (1963).

56. W. Th. A. M. van Der Lugt and L. J. Oosterhoff, Chem. Commun., 1235 (1968).

57. R. McDiarmid and E. Charney, J. Chem. Phys., 47, 1517 (1967).

58. J. C. D. Brand, J. Chem. Soc., 858 (1956).

59. R. Gerberich and W. D. Walters, J. Am. Chem. Soc., 83, 3935 (1960); 84, 4884 (1961).

60. M. O'Sullivan and A. C. Testa, J. Am. Chem. Soc., 90, 6245 (1968).

61. G. W. Robinson, J. Chem. Phys., 22, 1147 (1954).

62. F. Wilkinson and J. T. Dubois, J. Chem. Phys., 39, 377 (1963).

63. E. J. Bowen and A. H. Williams, Trans. Faraday Soc., $\underline{35}$, 765 (1939).

64. B. Radziszewski, Ann., $\underline{203}$, 305 (1880).

65. M. Trautz, Z. Phys. Chem., $\underline{53}$, 1 (1905).

66. V. Ya. Shlyapintokh, O. N. Karpukhin, L. M. Postnikov, V. F. Tsepalov, A. A. Vichutinskii and I. V. Zakharov, in "Chemiluminescence Techniques in Chemical Reactions", Plenum Publishing Corp., New York, N.Y., 1968, p. 3.

67. K. D. Gundermann, Angew. Chem. Intern. Ed. Engl., $\underline{4}$, 566 (1965).

68. F. McCapra, Q. Rev., $\underline{20}$, 485 (1966).

69. T. Goto and Y. Kishi, Angew. Chem. Intern. Ed. Engl., $\underline{7}$, 407 (1968).

70. E. H. White and M. J. C. Harding, Photochem. and Photobiol., $\underline{4}$, 1129 (1965).

71. F. McCapra and D. G. Richardson, Tetrahedron Letters, No. 43, 3167 (1964).

72. E. H. White and M. J. C. Harding, J. Am. Chem. Soc., $\underline{86}$, 5686 (1964).

73. F. H. Johnson, E. H. C. Sie and Y. Haneda, in "Light and Life", W. D. McElroy and B. Glass, Ed., The Johns Hopkins Press, Baltimore, 1961, p. 206.

74. Y. Kishi, S. Matsuura, S. Inoue, O. Shimomura, and T. Goto, Tetrahedron Letters, No. 24, 2847 (1968).

75. E. H. White, F. McCapra, G. F. Field and W. D. McElroy, J. Am. Chem. Soc., $\underline{83}$, 2402 (1961).

76. T. A. Hopkins, H. H. Seliger, E. H. White and M. M. Cass, J. Am. Chem. Soc., $\underline{89}$, 7148 (1967).

77. F. McCapra, Y. C. Chang and V. P. Francois, Chem. Commun., 22 (1968).

78. E. H. White, E. Rapaport, T. A. Hopkins and H. H. Seliger, J. Am. Chem. Soc., $\underline{91}$, 2179 (1969).

79. Y. Kishi, T. Goto, Y. Hirata and O. Shimomura, Tetrahedron Letters, No. 29, 3427 (1966).

80. F. McCapra and Y. C. Chang, Chem. Commun., 522 (1966).

81. F. McCapra and R. Wrigglesworth, Chem. Commun., 1256 (1968).

82. O. Shimomura and F. H. Johnson, Biochem., 7, 1734 (1968).

83. F. McCapra and R. Wrigglesworth, Chem. Commun., 91 (1969).

84. W. D. McElroy and H. H. Seliger, in "Light and Life", W. D. McElroy and B. Glass, Ed., The Johns Hopkins Press, Baltimore, 1961, p. 219.

85. F. McCapra and R. A. Hann, Chem. Commun., 442 (1969).

86. E. A. Chandross, Tetrahedron Letters, No. 12, 761 (1963).

87. M. M. Rauhut, Accounts of Chemical Research, 2, 80 (1969), and references therein.

88. M. A. A. Clyne and B. A. Thrush, Proc. Roy. Soc., (London), A269, 404 (1962).

89. M. Busch and W. Dietz, Ber., 47, 3277 (1914).

90. K. H. Pausacker, J. Chem. Soc., 3478 (1950).

91. E. P. Kohler and R. B. Thompson, J. Am. Chem. Soc., 59, 887 (1937).

92. W. H. Richardson and R. F. Steed, J. Org. Chem., 32, 771 (1967).

93. R. C. Fuson and H. L. Jackson, J. Am. Chem. Soc., 72, 1637 (1950).

94. W. von E. Doering and R. M. Haines, J. Am. Chem. Soc., 76, 482 (1954).

95. W. von E. Doering and J. D. Chanley, J. Am. Chem. Soc., 68, 586 (1946).

96. R. G. Pearson and D. N. Edgington, J. Am. Chem. Soc., 84, 4607 (1962).

97. C. E. Griffin and R. E. Lutz, J. Org. Chem., 21, 1134 (1956).

98. B. Witkop and J. B. Patrick, J. Am. Chem. Soc., 73, 2188 (1951); 73, 2194 (1951).

99. B. Witkop and J. B. Patrick, J. Am. Chem. Soc., 74, 3855 (1952).

100. R. J. S. Beer, L. McGrath and A. Robertson, J. Chem. Soc., 2118 (1950).

101. F. McCapra, D. G. Richardson and Y. C. Chang, Photochem. and Photobiol., 4, 1111 (1965).

102. H. Staudinger, Ber., 58, 1075 (1925).

103. E. F. Jenny, H. Droescher and A. Melzer, Angew. Chem. Intern. Ed., 3, 650 (1964).

104. K. Mayumi, O. Shibuya and S. Ichinose, Nippon Kagaku Zasshi, 78, 280 (1957).

105. F. R. Mayo, J. Am. Chem. Soc., 80, 2465 (1958).

106. H. J. Lucas, A. N. Prater and R. E. Morris, J. Am. Chem. Soc., 57, 723 (1935).

107. F. D. Gunstone and T. P. Hilditch, J. Chem. Soc., 1022 (1946).

108. D. Swern, J. E. Coleman, H. B. Knight, R. Ricciuti, C. O. Willits, and C. R. Eddy, J. Am. Chem. Soc., 75, 3135 (1953).

109. C. Paquot, Bull. Soc. Chim., (France), 12, 120 (1945).

110. C. S. Foote and J. Wei-Ping Lin, Tetrahedron Letters, No. 29, 3267 (1968).

111. C. S. Foote, Accounts of Chemical Research, 1, 104 (1968).

112. J. E. Huber, Tetrahedron Letters, No. 29, 3271 (1968).

113. G. O. Schenck. Angew. Chem., 69, 579 (1957).

114. W. Fenical, D. R. Kearns and P. Radlick, J. Am. Chem. Soc., 91, 3396 (1969).

115. E. H. White, J. Wiecko, D. Roswell and H. Doshan, J. Am. Chem. Soc., 91, 5194 (1969).

116. A. Rieche and W. Brunshagen, Ber., 61B, 951 (1928).

117. F. Feigl and V. Anger in "Spot Tests in Organic Analysis", translated by R. E. Oesper, Elsevier Publishing Co., Amsterdam, London, New York, 1966, p. 434.

118. D. H. Ballard, A. J. Bloodworth and R. J. Bunce, Chem. Commun., 815 (1969).

119. O. Blank and H. Finkenbeimer, Ber., 31, 2979 (1898).

120. P. Freon, Ann. Chim., 11, 453 (1939).

121. J. F. Froning and G. F. Hennion, J. Am. Chem. Soc., 62, 653 (1940).

122. E. M. McMahon, J. N. Roper, Jr., W. P. Utermohlen, Jr., R. H. Hasek, R. C. Harris, and J. H. Brant, J. Am. Chem. Soc., 70, 2971 (1948).

123. M. J. Jorgenson, Tetrahedron Letters, No. 13, 559 (1962).

124. A. Lauchenauer and H. Schinz, Helv. Chim. Acta, 34, 1514 (1951).

125. C. A. Grob and P. W. Schiess, Angew. Chem. Intern. Ed., 6, 1 (1968).

126. E. Koch, Tetrahedron, 24, 6295 (1968).

127. D. B. Sharp, Abstracts, 139th National Meeting of the American Chemical Society, New York, N.Y., Sept. 1960, p. 79P.

128. H. G. Smith and R. E. Rundle, J. Am. Chem. Soc., 80, 5075 (1958).

129. S. I. Chan, J. Zinn and W. D. Gwinn, J. Chem. Phys., 34, 1319 (1961).

130. Index of Mass Spectral Data, Special Techn. Publ. No. 356, American Society for Testing and Materials, Philadelphia, P.A., 1963.

131. A. Findlay in "Practial Physical Chemistry", Eighth Edition, Revised and Edited by J. A. Kitchener, Longmans, 1959, p. 107.

132. G. Herzberg in "Molecular Spectra and Molecular Structure. I. "Spectra of Diatomic Molecules", 2nd ed., D. Van Nostrand Co., New York, N.Y. 1950, p. 560.

133. A. M. Winer and K. D. Bayes, J. Phys. Chem., 70, 302 (1966).

134. A. Vallance-Jones and A. W. Harrison, J. Atmospheric Terrest. Phys., 13, 45 (1958).

135. R. M. Badger, A. C. Wright and R. F. Whitlock, J. Chem. Phys., 43, 4345 (1965).

136. G. Drefahl and C. Zimmer, Ber., 93, 505 (1960).

137. H. O. House, J. Am. Chem. Soc., 77, 3070 (1955).

138. C. G. Overberger and H. Gainer, J. Am. Chem. Soc., 80, 4556 (1958).

139. G. Cranck and F. W. Eastwood, Austr. J. Chem., 17, 1392 (1964).

140. G. P. Newsoroff and S. Sternhell, Australian J. Chem., 19, 1667 (1966).