FREE RADICAL REACTIONS IN SOLUTION

by

James David Irving B.Sc.,

Thesis presented for the degree of Doctor of Philosophy
University of Edinburgh September 1968

To

My Parents

and

Muriel

ABSTRACT

Phenylpropiolyl peroxide and its p-methyl-, p-methoxy-, p-chloro-, and p-bromo-substituted analogues have been synthesised in good yield and high purity by a method involving the reaction of the corresponding carboxylic acid with 98% hydrogen peroxide and dicyclohexylcarbodiimide.

The parent compound has been decomposed in a variety of solvents and the mechanism of induced decomposition in these solvents investigated.

The decomposition of the peroxides in chloroform at 65·0° in the presence of equimolar (0·05M) quantities of 3,4-dichlorostyrene to inhibit the induced decomposition enabled estimation of the first-order rate constants.

Application of the Arrhenius' equation to the data from decompositions carried out in chloroform at different temperatures enabled estimation of the energy of activation for the decomposition of the parent compound and the p-methyl- and p-methoxy- analogues. The p-methoxy compound had a greatly enhanced rate of decomposition and lower activation energy - suggesting a different mechanism and the possibility of a non-homolytic decomposition.

The synthesis of systems designed to differentiate between bridged and classical free radical intermediates by identification of the reaction products has been investigated.

The production of radicals of this nature from aldehydes and azo compounds was unsuccessful due to the difficulty experienced in synthesis of the starting materials.

The synthesis of 4-t-butyl-2-bromocyclohexylformyl peroxide has been achieved from the corresponding acid with 98% hydrogen peroxide and dicyclohexylcarbodiimide.

4-t-butyl-1-cyanocyclohexene was found to undergo stereospecific addition of hydrogen bromide to give exclusively the *trans* addition product, namely, *trans*-4-t-butyl-*cis*-2-bromo-1-cyanocyclohexane, under both free radical and ionic conditions. The significance of this in relation to bridged radicals is discussed.

The decomposition of the bromo peroxide did not give the expected products when investigated under similar conditions to those employed for the parent compound, 4-t-butylcyclohexylformyl peroxide. This limited the amount of information that could be obtained.

ACKNOWLEDGEMENTS

I should like to thank Dr. I.H. Sadler for his constant advice and encouragement throughout the course of this work.

Thanks are also due to the Science Research Council for the award of a Research Studentship and to Professor Sir Edmund L. Hirst for the provision of library and laboratory facilities.

Finally I should like to thank Mrs. Williams for typing this thesis.

Contents

Page

Part I

The synthesis and decomposition of phenylpropiolyl peroxides

1. Introduction

1.1. Dialkyl and diacyl peroxides 1

1.2. Kinetic studies 4

1.2.1. Benzoyl peroxide 4

1.2.2. Substituted benzoyl peroxides 10

1.2.3. Miscellaneous peroxides 12

1.3. The object of the research 14

2. Experimental

2.1. Introduction 15

2.2. Purification of solvents 15

2.3. The synthesis of phenylpropiolyl peroxide 16

2.4. Peroxide estimation 20

2.5. The synthesis of p-substituted phenylpropiolyl peroxides 21

2.6. Gas-liquid chromatography 24

2.6.1. Preparation and purification of materials 24

2.6.2. Instrumentation 26

2.6.3. Measurement of retention times 27

2.7. The products of the decomposition of phenylpropiolyl peroxide in various solvents 28

2.8. The kinetics of the decomposition of phenylpropiolyl peroxide in various solvents 32

2.8.1. Introduction 32

2.8.2. Preliminary experiment in cumene 33

2.8.3. Kinetic studies in solutions of varying concentration at 65·0° 34

2.9. The kinetics of the decomposition of phenylpropiolyl peroxide in the presence of an inhibitor 49

Page
2.9.1. The decomposition in the presence of styrene 49
2.9.2. The decomposition in the presence of 3,4-dichlorostyrene 53
2.9.3. Estimation of the energy of activation 60
2.10. Kinetic studies of p-substituted phenylpropiolyl peroxides 61

3. Discussion

3.1. The synthesis of phenylpropiolyl peroxide and p-substituted analogues 67
3.2. The products of the decomposition of phenylpropiolyl peroxide in various solvents 68
3.3. The kinetics of the decomposition 72
3.4. The kinetics in the presence of an inhibitor at $65{\cdot}0^{\circ}$ 78
3.5. The decomposition of p-substituted phenylpropiolyl peroxides in chloroform 82
3.6. Conclusion 84

Part II

Stereospecificity in free radical reactions

1. Introduction

1.1. The concept of bridged radicals 85
1.2. Addition reactions to olefins 85
1.3. Halogenation of substituted alkanes 99

2. Discussion

2.1. The object of the research 106
2.2. The attempted syntheses of trans,4,4'-di-t-butyl-2,2',-dibromoazocyclohexane and trans-4-t-butyl-cis-2-bromocyclohexane-1-carboxaldehyde 107
2.3. The addition of hydrogen bromide to 4-t-butyl-1-cyanocyclohexene; 4,4'-dimethyl-1-cyanocyclohexene and 4-t-butylcyclohexene 109

Page

2.4. The synthesis and decomposition of di-*trans*-4-t-butylcyclohexylformyl and di-*trans*-4-t-butyl-*cis*-2-bromocyclohexylformyl peroxides 114

3. Experimental

3.1. Introduction 120

3.2. The synthesis of 4-t-butyl-2-bromo-1-cyanocyclohexane 120

3.3. Hydrolysis of the nitrile with aqueous acid 126

3.4. The reduction of nitrile to aldehyde 127

3.5. The peroxide syntheses 130

3.6. The preparation of 4- and 3-t-butyl-1-bromocyclohexane 132

3.7. The synthesis of 4,4-dimethyl-1-cyanocyclohexene 135

3.8. Hydrogen bromide additions 136

3.9. Gas-liquid chromatography 137

3.10. Peroxide decompositions 139

Bibliography 142

PART I

The synthesis and decomposition of phenylpropiolyl peroxides

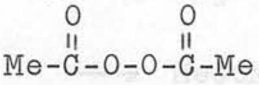
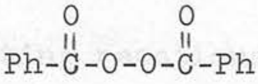
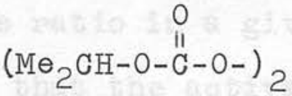
SECTION 1

Introduction

1.1. Dialkyl and diacyl peroxides

The formation of free radicals by the thermal cleavage of covalent bonds below 150°C requires a structure stable to competing heterolytic processes and possessing a weak covalent bond with a dissociation energy in the region of 20 - 40 Kcal. mole^{-1}. The most frequently encountered compounds are those possessing the peroxidic O-O bond. Some of the more commonly used peroxides are listed in Table I, together with their activation energies for decomposition and the temperature at which their half-life is one hour.

Table I. Typical peroxide initiators

Name	Structure	$E_{act.}$ Kcal.mole^{-1}	°C for $t_{\frac{1}{2}}$=1hr.	Ref.
Di-t-butyl peroxide	$Me_3CO\text{-}OCMe_3$	34	150	1
Diacetyl peroxide	 $Me\text{-}\overset{O}{\overset{\parallel}{C}}\text{-}O\text{-}O\text{-}\overset{O}{\overset{\parallel}{C}}\text{-}Me$	29·5*	85*	2
Dibenzoyl peroxide	 $Ph\text{-}\overset{O}{\overset{\parallel}{C}}\text{-}O\text{-}O\text{-}\overset{O}{\overset{\parallel}{C}}\text{-}Ph$	30*	95*	3
Diisopropyl peroxy dicarbonate	 $(Me_2CH\text{-}O\text{-}\overset{O}{\overset{\parallel}{C}}\text{-}O\text{-})_2$	24	58*	4

* Solvent dependent; data given for inert solvents.

Peroxides have been employed for the initiation of substitution, addition and polymerisation reactions all of which have been reviewed in detail. The present review is mainly concerned with the kinetics and mechanism of peroxide decompositions.

Two of the major pathways of peroxide decomposition, unimolecular scission of the peroxidic 0-0 bond and radical induced decomposition are conveniently illustrated by di-t-butyl peroxide (I). Since it is relatively stable it has been studied in greater detail than the other dialkyl peroxides. It decomposes at essentially the same rate in the gas phase[5] and in a variety of solvents[6] suggesting that the majority of the peroxide decomposes by a unimolecular process to give t-butoxy radicals (II) which may react with a hydrogen donor solvent to give t-butanol. However, at temperatures above 110°, the overall course is more complicated as the t-butoxy radicals readily decompose to acetone and methyl radicals.

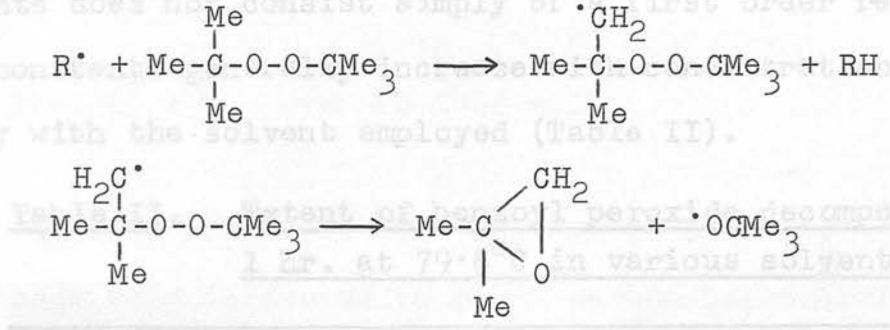
$$\underset{\text{I}}{\mathrm{Me_3C{-}O{-}O{-}CMe_3}} \longrightarrow \underset{\text{II}}{\mathrm{2Me_3C{-}O^{\bullet}}}$$

$$\mathrm{Me_3C{-}O^{\bullet} + RH \longrightarrow Me_3C{-}OH + R^{\bullet}}$$

$$\mathrm{Me_3C{-}O^{\bullet} \longrightarrow MeCOMe + Me^{\bullet}}$$

The last two are competing reactions and in general, values of the t-butyl alcohol:acetone ratio in a given system decrease with temperature indicating that the activation energy for the t-butoxy radical decomposition is considerably higher than that for hydrogen abstraction. The ratio increases as the solvent becomes a better hydrogen donor.

In pure liquid di-t-butyl peroxide, where the peroxide acts as solvent the decomposition is in part induced by a bimolecular reaction of the peroxide and either methyl or t-butoxy radicals resulting from the unimolecular process. This is suggested by the identification of isobutylene oxide[7] among the products, and the higher rate of peroxide decomposition.



$$R^{\bullet} + Me\text{-}C(Me)_2\text{-}O\text{-}O\text{-}CMe_3 \longrightarrow Me\text{-}C(Me)(^{\bullet}CH_2)\text{-}O\text{-}O\text{-}CMe_3 + RH$$

(R = Me$^{\bullet}$ or t-BuO$^{\bullet}$)

A third decomposition pathway, namely, detonation has received little study beyond the observation[8] that detonation may be caused by heat shock or friction. In general the stability of peroxides increases as the percentage of oxygen in the molecule decreases.

Of the diacyl peroxides, benzoyl and acetyl peroxides have been extensively studied especially the former whose decomposition was first formulated as a free radical process by Hey[9] and Wieland.[10]

However, in spite of its importance the complexity of its decomposition makes it not altogether an ideal initiator for mechanistic studies and many of its reactions are still the subject of research.[11,12]

1.2. Kinetic Studies

1.2.1. Benzoyl Peroxide

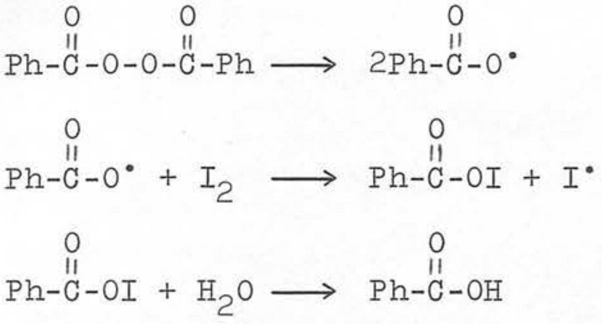
Kinetically, the decomposition of benzoyl peroxide in most solvents does not consist simply of a first order reaction as the rate constants generally increase with concentration and vary widely with the solvent employed (Table II).

Table II. Extent of benzoyl peroxide decomposition after 1 hr. at 79·8°C in various solvents.[13]

Solvent	% decomposed
Carbon Tetrachloride	13·5
Benzene	15·5
t-butylbenzene	28·5
Cyclohexane	51·0
Dioxane	82·4
Aniline	explosive reaction

This suggests appreciable induced decomposition but even when an attempt is made to eliminate this using radical traps[13] such as styrene or 3,4-dichlorostyrene which inhibit the induced process, the rate is still dependent on solvent although the activation energy remains constant (*ca.*, 30 Kcal.mole^{-1}) within experimental error.

The decomposition[14] in moist carbon tetrachloride in the presence of iodine demonstrates the initial scission. The iodine supresses induced decomposition but is without other effect on the decomposition rate and the benzoyl peroxide appears quantitatively as benzoic acid via the sequence:-



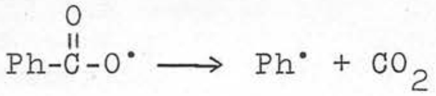
$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}Ph \longrightarrow 2Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet}}$$

$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet} + I_2 \longrightarrow Ph{-}\overset{O}{\overset{\|}{C}}{-}OI + I^{\bullet}}$$

$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}OI + H_2O \longrightarrow Ph{-}\overset{O}{\overset{\|}{C}}{-}OH}$$

No benzoic acid is formed in moist carbon tetrachloride in the absence of iodine.

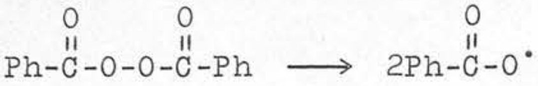
As in the case of di-t-butyl peroxide, the radical initially formed may break down to give a neutral molecule and a smaller radical:-



$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet} \longrightarrow Ph^{\bullet} + CO_2}$$

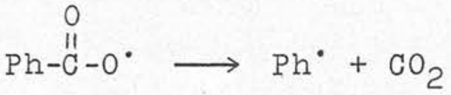
This process competes with attack of the intermediate benzoyloxy radical on other substrates in the reaction system. In general, carbon dioxide yields increase with solvents in the order olefins < saturated hydrocarbons < aromatic hydrocarbons < carbon tetrachloride, and also with increasing temperature,[15] suggesting that the activation energy for the decomposition of the benzoyloxy radical must be higher than for the rate of attack of this radical on the solvent. However, the situation is complicated by induced decompositions.

These have been the subject of intensive study since first deduced by Nozaki and Bartlett[13] and Cass[16] from the observations that the apparent unimolecular rate constant increases with peroxide



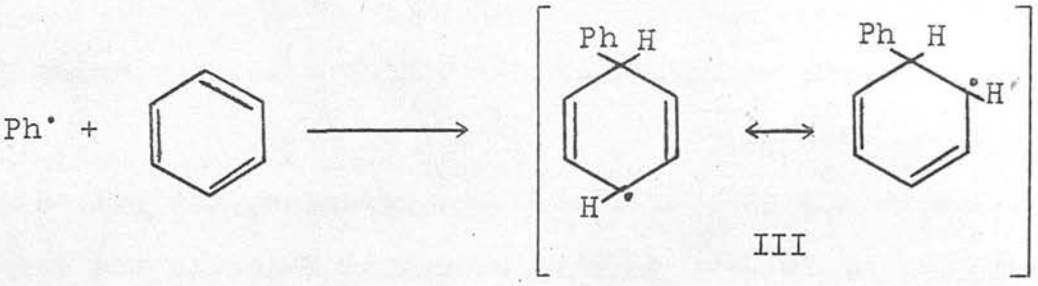
$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}Ph \longrightarrow 2Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet}}$$

(a)

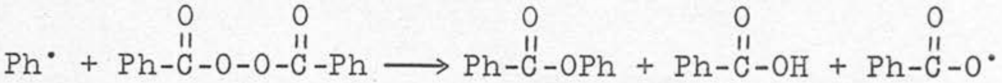


$$\mathrm{Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet} \longrightarrow Ph^{\bullet} + CO_2}$$

(b)

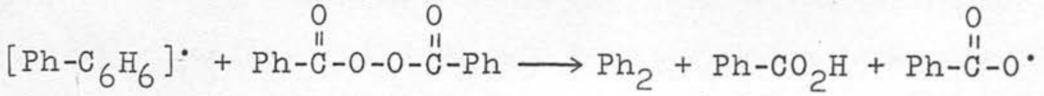


(c)



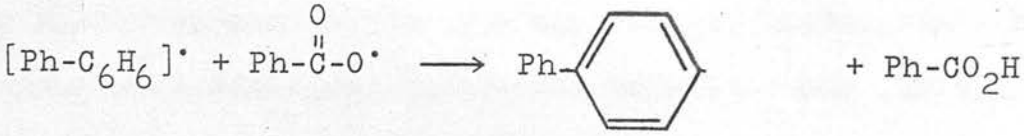
$$\mathrm{Ph^{\bullet} + Ph{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}Ph \longrightarrow Ph{-}\overset{O}{\overset{\|}{C}}{-}OPh + Ph{-}\overset{O}{\overset{\|}{C}}{-}OH + Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet}}$$

(d)

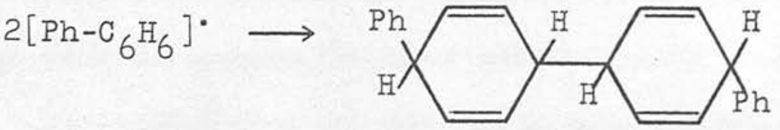


$$\mathrm{[Ph{-}C_6H_6]^{\bullet} + Ph{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}Ph \longrightarrow Ph_2 + Ph{-}CO_2H + Ph{-}\overset{O}{\overset{\|}{C}}{-}O^{\bullet}}$$

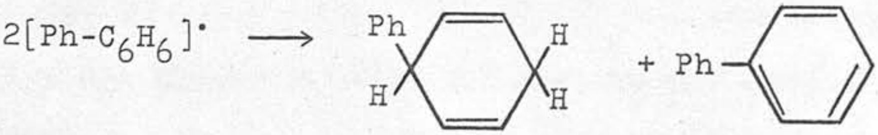
(e)



(f)



(+ isomers) (g)



(h)

concentration, and that the rate is increased by added radical sources and decreased by oxygen and typical inhibitors such as quinones.

In the kinetic equation (i), the induced decomposition,

$$\frac{-d[P]}{dt} = k_1[P] + k_2[P]^{3/2} \text{ .... (i)}$$

expressed in the term $k_2[P]^{3/2}$, gives rise in general to a variation in the observed rate of reaction from one solvent to another and is derived from the scheme:-

$$P \xrightarrow{k_1} 2R$$

$$2R \xrightarrow{k_2} RR$$

$$R + P \xrightarrow{k_3} X + R$$

(where P = peroxide; R = any free radical; X = Product(s) from the chain decomposition).

Recent investigations of the decomposition of benzoyl peroxide in alkyl benzenes[17] and in benzene[18] have shown that in these solvents the cyclohexadienyl radical (III), produced in step (c) in the scheme opposite, is mainly responsible for bringing about the induced decomposition. Evidence for the proposed scheme also comes from the observed variation of yields of the reaction products over a wide range of initial peroxide concentrations.[19,20] Yields of biphenyl, dihydrobiphenyl and benzoic acid show very marked variation in the low concentration range of peroxide and extrapolation to infinite dilution of a plot of yield versus peroxide concentration suggests that the yield of benzoic acid would be virtually zero and the yields of biphenyl and dihydrobiphenyl equal, i.e. their exclusive formation would result from the disproportionation reaction (h).

Gill and Williams,[18] deduce the rate equation (ii) from a study of the phenylation of substituted aromatic hydrocarbons with benzoyl peroxide.

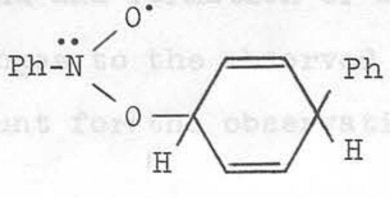
$$\frac{-d[P]}{dt} = k_1[P] + k_I[P] + k_{3/2}[P]^{3/2} \;\ldots\ldots\ldots\; \text{(ii)}$$

The first term is small and is due to the first order scission; the second two terms, due to the induced decomposition show components which are either first or three-halves order in peroxide concentration depending on whether termination is by process (f) or by processes (g) and (h), respectively.

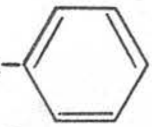
In pure bromobenzene, the importance of (f) is revealed both by the kinetics and by the low yields of products of high molecular weight arising from path (g).

The results with nitrobenzene and with benzene containing 1% nitrobenzene are closely similar. Both show first-order induced decomposition over the whole concentration range studied, together with a three-halves order component at initial peroxide concentrations below 0·06M. In this "nitro-group effect", phenylcyclohexadienyl radicals are considered to be intercepted by nitrobenzene and the resulting adduct is then thought to induce the decomposition of a peroxide molecule.

$[Ph\text{-}C_6H_6]^{\cdot} + PhNO_2 \longrightarrow$

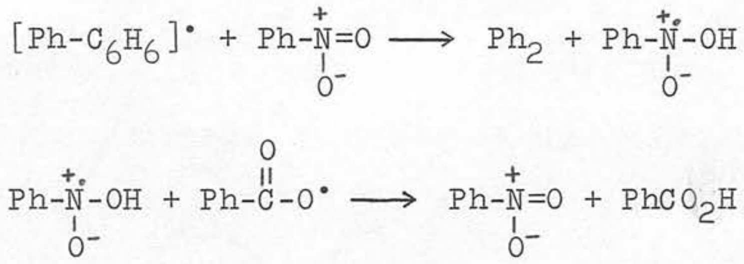


IV

$\mathrm{IV} + (\mathrm{PhCO_2})_2 \longrightarrow \mathrm{PhNO_2} + \mathrm{PhCO_2H} + \mathrm{PhCO_2}^\bullet + \mathrm{Ph}$- 

In the presence of nitro-compounds the yields of both biaryl and benzoic acid are increased at the expense of the high molecular weight by-products; this greatly enhances the preparative value of the reaction for the synthesis of biaryls.[12]

An alternative scheme has been proposed[21] involving addition of a hydrogen atom to one of the oxygen atoms of the nitro group:-



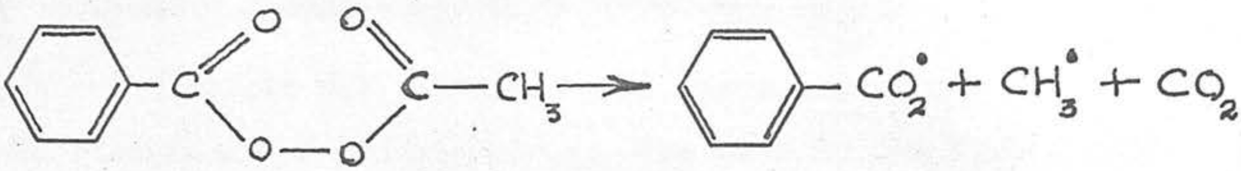
$$[\mathrm{Ph\text{-}C_6H_6}]^\bullet + \mathrm{Ph}\text{-}\underset{\mathrm{O^-}}{\overset{+}{\mathrm{N}}}\mathrm{=O} \longrightarrow \mathrm{Ph_2} + \mathrm{Ph}\text{-}\underset{\mathrm{O^-}}{\overset{+\bullet}{\mathrm{N}}}\mathrm{\text{-}OH}$$

$$\mathrm{Ph}\text{-}\underset{\mathrm{O^-}}{\overset{+\bullet}{\mathrm{N}}}\mathrm{\text{-}OH} + \mathrm{Ph}\text{-}\overset{\overset{\mathrm{O}}{\|}}{\mathrm{C}}\text{-}\mathrm{O}^\bullet \longrightarrow \mathrm{Ph}\text{-}\underset{\mathrm{O^-}}{\overset{+}{\mathrm{N}}}\mathrm{=O} + \mathrm{PhCO_2H}$$

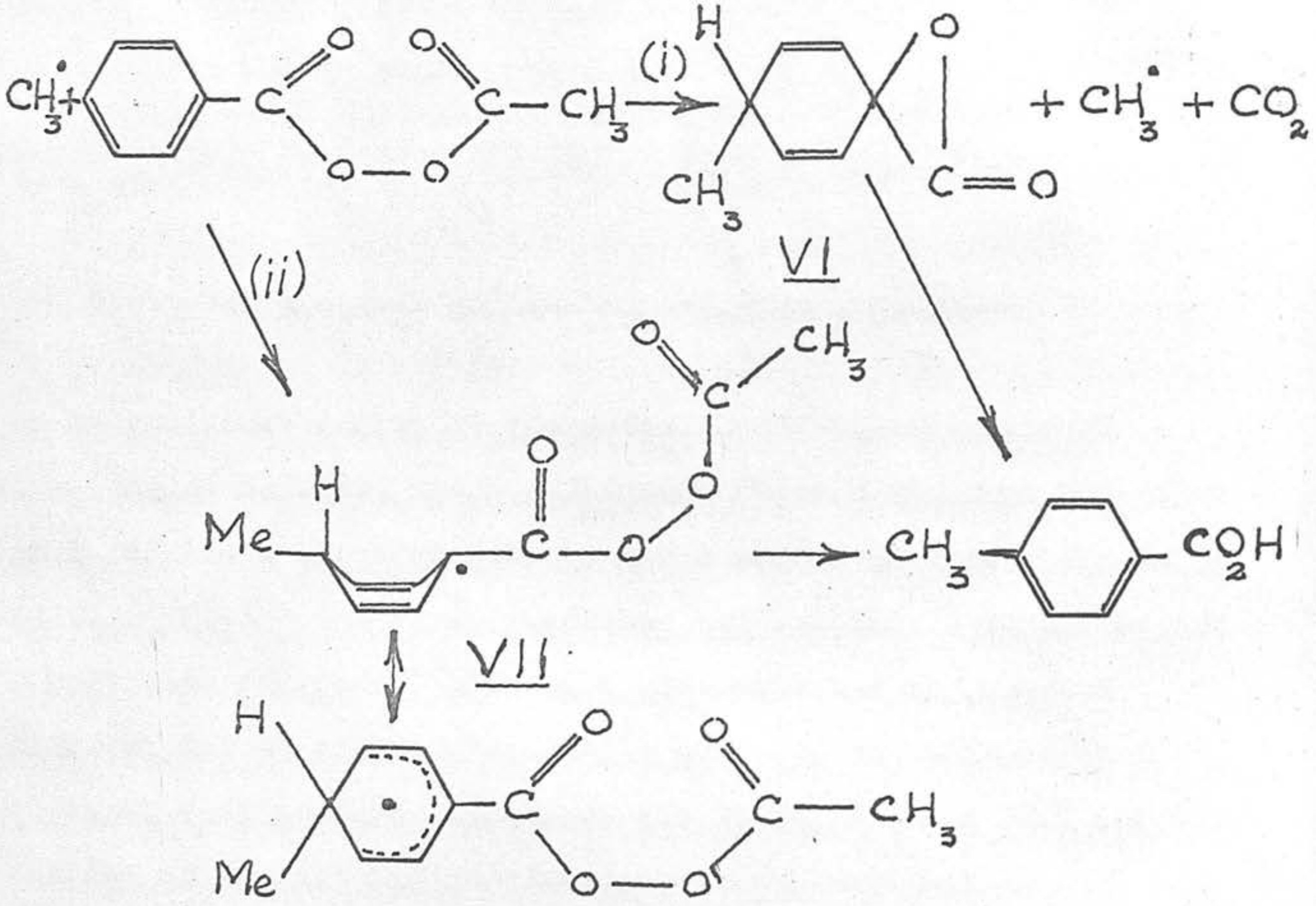
In both schemes the nitrobenzene in effect functions as an oxidising agent in a self-propagating chain reaction which results in higher yields of biphenyl and benzoic acid and a reduction in the amount of higher boiling residue.

However, it has also been suggested[21] that the reduction products of nitrobenzene have a catalytic effect on the reaction and the full elucidation of the mechanism requires further study.

The o- and p-substituted benzoic acids obtained by Walling and Savas[22] in the induced decomposition of benzoyl peroxide in benzene lead to the suggestion that at least one path for the induced chain is radical addition to the aromatic system together with concerted cleavage of the 0-0 bond and formation of an α-lactone structure (VI) which rearranges to the observed product. The scheme is also proposed[23] to account for the observation that

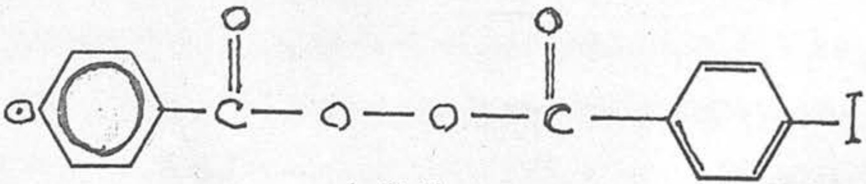


V



VI

VII



VIII

the major products of the induced decomposition of acetyl benzoyl peroxide (V) - absent in the unimolecular reaction - are o- and p-toluic acids arising from methyl radical attack on the aromatic ring by path (i) in the scheme on facing page.

The alternative process (path (ii)), involving the intermediate radical (VII) - which can exist in two resonance forms - is analogous to that proposed[24] to account for the formation of p-trichloromethylbenzoic acid in the decomposition of benzoyl peroxide in bromotrichloromethane. In this case, the intermediate radical undergoes homolysis of the peroxy-bond with concerted hydrogen abstraction to give the corresponding acid in one stage.

The generation[25] of (VIII) by the decomposition of bis(p-iodobenzoyl) peroxide in carbon tetrachloride at 80°C results in equivalent yields of p-diiodo- and p-dichlorobenzenes. p-diiodobenzene can come from p-iodophenyl attack either on the peroxide itself, leading to (VIII) or on p-chloroiodobenzene. On investigation of the peroxide after 15% decomposition the p-iodo-substituents in the undecomposed peroxide were found to have been replaced by p-chloro-substituents to an extent equivalent to approximately 42% of peroxide decomposed. Thus, the para-σ radical substituted peroxide (VIII) is formed without concerted decomposition of the peroxide and persists long enough to abstract chlorine from the solvent, but does not bring about induced decomposition.

Recently, Brydon and Cadogan[26] in a study of the decomposition of benzoyl peroxide in iodobenzene report a first order rate constant similar to that for the decomposition in bromobenzene.[18] This points to a similar mechanism of decomposition of the peroxide in both solvents, i.e. the absence of an additional mode of decomposition arising from the presence of iodobenzene.

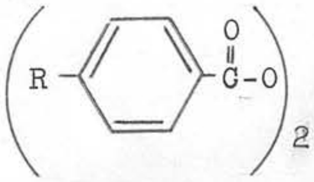
A theoretical study of the elementary steps involved in the decomposition of benzoyl peroxide in benzene has been undertaken by DeTar.[27] In this, mechanisms (consisting of the equations, together with the rate constants for each, and the initial concentration) based on several sets of 200-300 elementary steps have been evaluated quantitatively by computer techniques and the minor reactions eliminated on the basis of demonstrated unimportance. A resulting set of about 100 elementary steps gave good quantitative correlations between observed and calculated product yields as a function of peroxide concentration. The study emphasises the complex nature of benzoyl peroxide decompositions, and introduces a novel approach to solving kinetic problems.

1.2.2. Substituted benzoyl peroxides

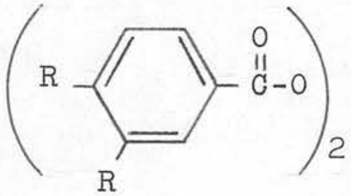
The decompositions[3] of the substituted benzoyl peroxides (IX, X, XI) in dioxane were investigated in the presence of 0·2M 3,4-dichlorostyrene to inhibit the induced reaction. (This was found to be the best of 39 inhibitors tested). The results were applied to the Hammett equation (iii) and gave a good $\sigma\rho$ plot with $\rho = -0{\cdot}38$

$$\log \frac{k}{ko} = \sigma\rho \quad \ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

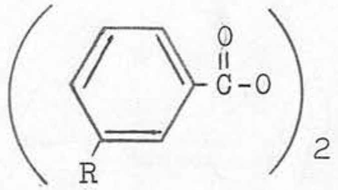
(where k is the 1st order rate constant for a phenyl compound containing a m- or p-substituent; k_o is the corresponding rate constant for the unsubstituted compound; σ is a constant characteristic of only the substituent and ρ is a constant characteristic of only the reaction).



IX



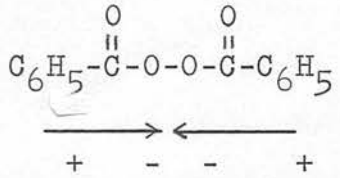
X



XI

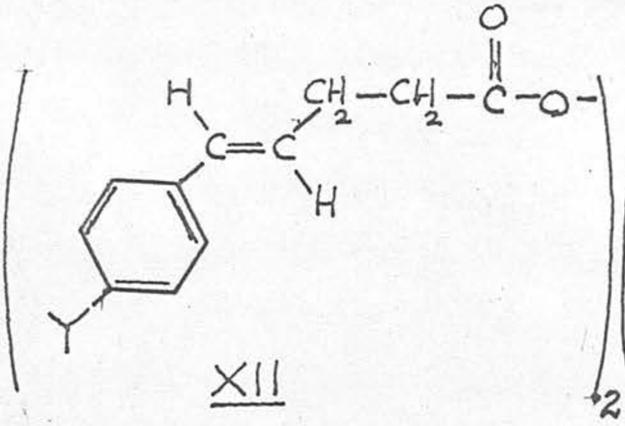
R = MeO; Me, $-NO_2$, -CN, -Br, -Cl

Electron withdrawing groups were found to decrease the rate and vice versa.



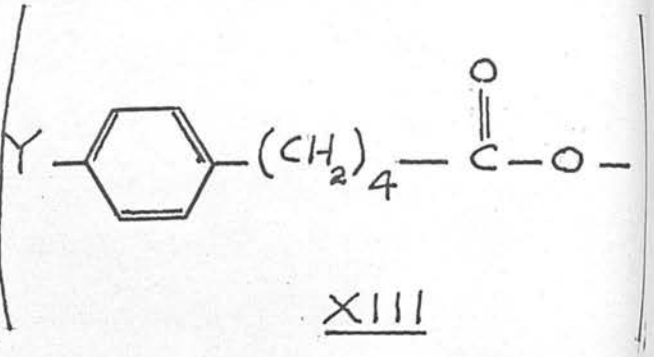
$C_6H_5-\overset{O}{\overset{\|}{C}}-O-O-\overset{O}{\overset{\|}{C}}-C_6H_5$

This is rationalised by assuming the two benzoate groups in benzoyl peroxide are dipoles attached together in such a way that they repel one another. The partial negative charges on the two central oxygen atoms are increased by electron repelling substituents and decreased by electron attracting substituents, but not enough so that the effective charge on oxygen becomes zero or its sign changes. Therefore, p-methoxy groups increase the rate by increasing the electrostatic repulsion between the benzoate groups which makes it easier for them to break apart into two benzoate radicals. The



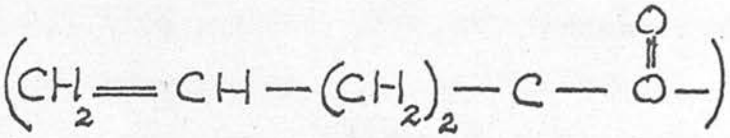
XII

Y = H, Cl, F, Me, OMe



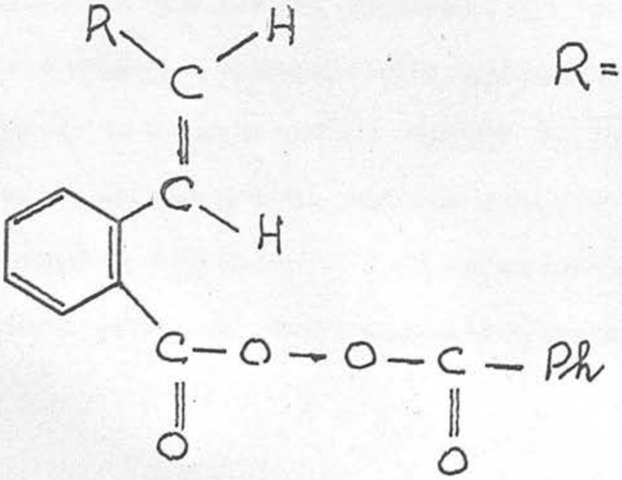
XIII

Y = H, OMe



$$\left(CH_2{=}CH-(CH_2)_2-C-\overset{\overset{O}{\|}}{O}-\right)$$

XIV



R=H, *m-and-p nitrophen*

XV

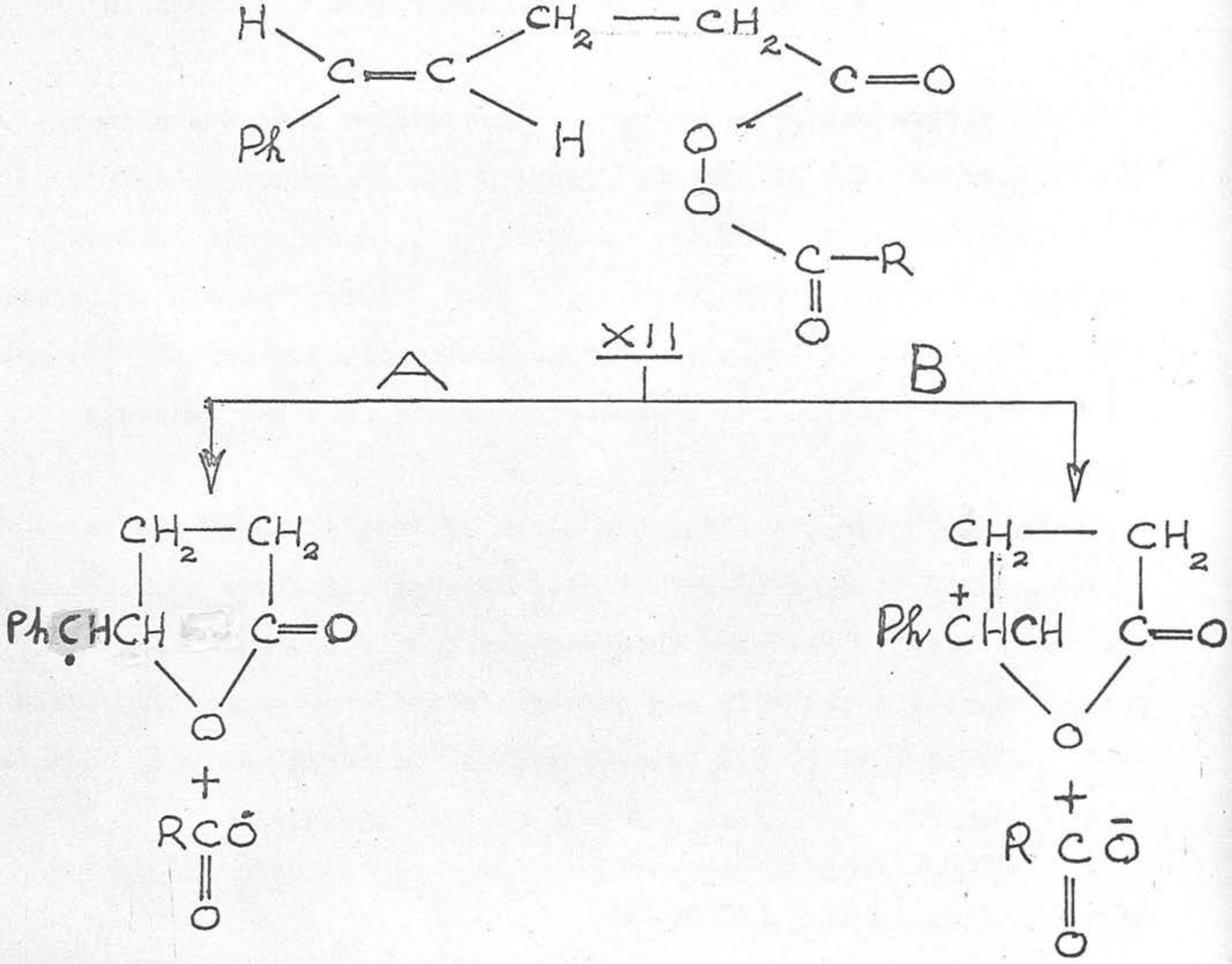
electron attracting substituents conversely have the opposite effect.

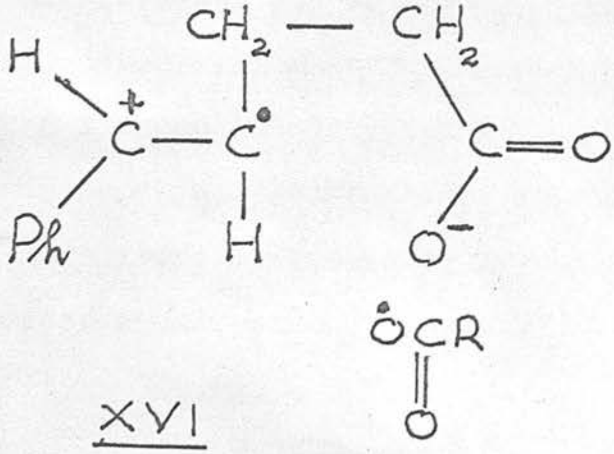
This view was enhanced by the observation that the unimolecular decomposition of benzoyl peroxide (in presence of inhibitor) varied in different solvents, being slowest in non-polar solvents and accelerated by polar solvents. Thus, benzoyl peroxide cleaves easily into free radicals by a unimolecular process largely because this relieves electrostatic repulsion between the two benzoate groups.

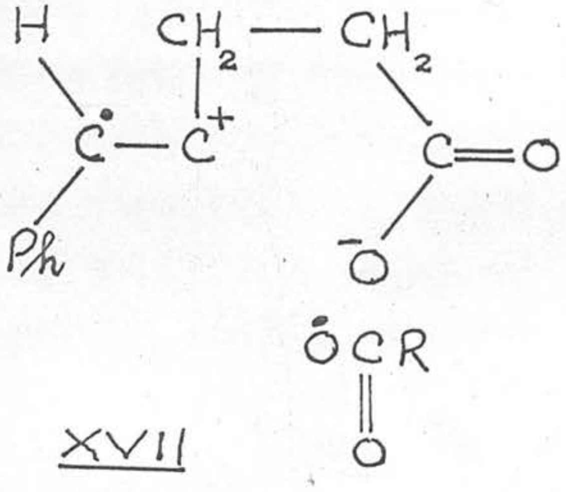
Cooper[28] investigating the rates of initiation of the polymerisation of styrene by substituted benzoyl peroxides corroborated the above results with the observations that electron releasing groups increased the rate and electron attracting groups decreased it. Substituents in the ortho position increased the rate because of a combination of steric and polarisation effects.

1.2.3. Miscellaneous Peroxides

Kinetic studies[29] on the three peroxides, trans-γ-benzylidenbutyryl peroxide (XII); δ-phenylvaleryl peroxide (XIII) and 4-pentenoyl peroxide (XIV) in benzene and propylene carbonate using the excess stable free radical technique lead to the observations that whereas the rates of decomposition of peroxide (XIV) and peroxides of type (XIII) are similar, the rates of decomposition of type (XII) are significantly greater - indicating that both the double bond and the aromatic ring are necessary to obtain the rate enhancement. Moreover, whereas there is little ring substituent


XII


XVI


XVII

effect on the decomposition rates of type (XIII) there is a significant ring substituent effect in the case of type (XII), where a Hammett $\sigma\rho$ plot for the decomposition in benzene at 50° – in which log k_d values were plotted against σ^+ – gave $\rho = -1{\cdot}16$. This is intermediate between the value of $\rho = -1{\cdot}8$ reported by Koenig and Martin[30] for compounds of type (XV) in chlorobenzene at 70° and that observed by Greene <u>et al.</u>[31] for the intermolecular reaction between substituted <u>trans</u>-stilbenes and benzoyl peroxide ($\rho = -1{\cdot}0$).

The rate enhancement of (XV) relative to unsubstituted benzoyl peroxide is ascribed to neighbouring group participation by the olefinic groups in the homolytic cleavage of the O-O bond. A similar mechanism involving cyclic intermediates formed via neighbouring group participation of the double bond was proposed to account for the fact that (XII) decomposes five times as fast as (XIII) in carbon tetrachloride containing styrene (10%) (See scheme on facing page).

The observation that increase in solvent polarity has a more pronounced effect on (XII) than (XIII), was rationalised by the postulation of the intermediacy of the charged structures (XVI) and (XVII), in the homolytic decomposition of (XII). (Path A). The kinetic data also suggested a greater difference in polarity between the transition states for the two peroxides, indicating that electron density is displaced from the double bond to the peroxide linkage in the transition state for the homolytic decomposition of type (XII).

1.3. The object of the research

The absence* of data in the literature on diacyl peroxides containing an acetylenic linkage prompted the synthesis of peroxides of this type with a view to investigating the effect of the linkage on the reactivity of the compounds.

Phenylpropiolyl peroxide was chosen since the phenyl group should introduce stability to the molecule, moreover the transmission of the electronic effect of m- and p-substituents (and possibly ortho as well) through the triple bond could be studied without interference from steric considerations.

---

* Since the completion of this work, a brief communication[37] has appeared. This is discussed later.

SECTION 2

Experimental

2.1. Introduction

Liquids and solutions were dried over magnesium sulphate before distillation or solvent removal.

Infra-red spectra (i.r.) were recorded on a Unicam SP200 instrument. Samples were examined at room-temperature (17-23°) as nujol mulls or as solutions in chloroform or carbon disulphide.

Nuclear magnetic resonance spectra (n.m.r.) were recorded on a Perkin-Elmer R10 (60 m/c) instrument. Samples were examined at 33° as pure liquids or as solutions (5-20%) in deuterochloroform or carbon tetrachloride. Chemical shifts (τ) are expressed relative to that for tetramethylsilane which is taken to be 10 p.p.m.

Abbreviations used in the quoting of spectroscopic data are;
i.r.: (s), strong absorption; (m), medium; (w), weak.
n.m.r.: (s), singlet; (d), doublet; (m), multiplet.

The literature values for physical constants marked with an asterisk (i.e. Lit.*,) were taken from "The Dictionary of Organic Compounds"; Eyre and Spottiswood; London, 1965.

2.2. Purification of solvents

Benzene (b.p. 80°) and Cumene (b.p. 152°) were washed with sulphuric acid (Sp.Gr. 1·84) until the acid layer was colourless, and then with water. They were dried before distillation and stored over sodium wire.

Toluene (b.p. 111°) was washed in turn with sulphuric acid (Sp.Gr. 1·84), 10% aqueous sodium hydroxide and then water, and dried before distillation. It was stored over sodium wire.

Carbon tetrachloride (b.p. 77°) was boiled for 1-2 hours, with 5% aqueous sodium hydroxide, dried, distilled and stored over magnesium sulphate.

Chloroform (b.p. 61°) was washed with water, dried, distilled and stored over magnesium sulphate. It was passed through an alumina column immediately before use.

Dioxane (b.p. 101-105°) was digested with dilute hydrochloric acid then dried with potassium hydroxide pellets. It was fractionated and stored over sodium wire.

Cyclohexane (b.p. 81°) was passed through an alumina column before distillation and stored over sodium wire.

These solvents were deoxygenated by passing a stream of dry nitrogen gas through them for two hours and then storing under nitrogen.

2.3. The synthesis of phenylpropiolyl peroxide

Ethyl-α, β-dibromo-β-phenylpropionate was synthesised from ethyl cinnamate (262 g. 1·49 moles) and bromine (263 g. 1·65 moles) in cold carbon tetrachloride according to the method of Abbott.[32] The yield of crude material was 97%; m.p. 69-70° (Lit.*, 65-71°). This was used for the next stage without further purification.

Phenylpropiolic acid was prepared[32] by dehydrobromination of ethyl-α, β-dibromo-β-phenylpropionate (487 g. 1·45 moles) with ethanolic potassium hydroxide (365 g. 6·52 moles). Recrystallisation of the crude acid (92%) from carbon tetrachloride gave colourless needles m.p. 135-136°. (Lit.*, 135-136°).

In subsequent preparations, the literature scheme was modified. After boiling with ethanolic potassium hydroxide, the solvent was removed by distillation and the residue dissolved in cold water. This was acidified with concentrated hydrochloric acid and the phenylpropiolic acid extracted with ether. This gave consistently higher yields of the acid (ca. 95%).

The acid was also prepared from cinnamic acid (148 g. 1·0 mole) by the addition of bromine (160 g. 1·0 mole) in boiling carbon tetrachloride according to the method of Reimer.[33] The α,β-dibromo-β-phenylpropionic acid so formed was dehydrobrominated as above to yield phenyl propiolic acid in 95% yield.

Phenylpropiolyl chloride was prepared by refluxing phenylpropiolic acid with excess thionyl chloride for two hours and removing the excess thionyl chloride by distillation. The residue (75% yield) was redistilled b.p., 86-90°/0·6 m.m. (Lit.*, 115-116°/17 m.m.).

Phenylpropiolyl peroxide was prepared from the acid chloride by the method of DeTar and Wells[34] ((a) below) and from phenylpropiolic acid (b) by the method of Greene[35] et al.

The peroxide was stable when pure and kept cold. It was stored at -20°. On warming the solid above room temperature or on grinding or scraping, detonation was immediate. A spontaneous autoaccelerative decomposition, preceded by bubbling and frothing of the sample, occurred on two occasions when impure, yellow peroxide was allowed to warm to room temperature. This was accompanied by the release of acrid fumes and the deposition of tar.

In view of the danger involved, preparations were carried out behind a perspex safety shield. Goggles and rubber gloves were worn when handling the solid material.

The melting points quoted for the various peroxides are those temperatures at which a violent decomposition took place.

a) A solution of phenylpropiolyl chloride (10 g. 0·06 moles) in ether (50 ml.) was added dropwise over a period of 1 hr., to a solution of sodium peroxide (10 g. 0·13 moles) in ice-water (300 ml.). The reaction flask was cooled in an ice-water bath to maintain the temperature below 5°.

During the addition a yellow opaque oil settled out. The mixture was transferred to a separating funnel and shaken vigorously for a few minutes. The organic material was extracted with ether (100 ml.), washed with cold aqueous sodium bicarbonate (50 ml.), water (50 ml.) and dried. The volume of solvent was reduced to <u>ca</u>. 30 ml. by passing a stream of dry nitrogen gas through the solution.

The white solid peroxide was separated by decantation of the mother liquor, washed by decantation with ether (20 ml.) and dried by removal of solvents <u>in vacuo</u> (1 m.m.).

Yield, 1·0 g. (6%). Purity, 96%.

The low yield obtained in the above experiment persisted throughout a series of experiments with varying quantities of acid chloride and sodium peroxide. Changing the solvent to the low boiling trichloro fluoromethane and using hydrogen peroxide[36] instead of sodium peroxide resulted in an impure yellow product.

These investigations were not pursued further because of the dangerous nature of the impure product.

b) Hydrogen peroxide (99·9%; 1·5 ml. 2·28 g. 0·067 moles) and redistilled methylene chloride (25 ml.) were added to an ethereal solution (10 ml.) of N, N'-dicyclohexylcarbodiimide (2·48 g. 0·014 moles) in a conical flask immersed in an ice bath. The temperature was maintained below 5° during the careful, slow addition of finely powdered phenylpropiolic acid (2 g. 0·014 moles). After stirring the mixture for ½ hr., the dicyclohexyl urea (2·55 g. 95%) was removed by filtration with a sintered glass funnel and washed by slurrying with methylene dichloride (3 x 25 ml.), the washings being added to the filtrate. Ether (100 ml.) was added to the filtrate and the whole washed with cold saturated aqueous ammonium sulphate (3 x 25 ml.), cold 10% sodium bicarbonate solution (2 x 25 ml.), saturated sodium chloride solution (2 x 25 ml.), and dried.

The volume of the organic phase was reduced to <u>ca.</u>, 50 ml. by passing a stream of dry nitrogen through the solution. The mother liquor was decanted and the solid peroxide, after washing by decantation with methanol (5 ml.) and ether (5 ml.), was freed of all solvents *in vacuo* (1 m.m.). Further concentration of the mother liquor in a similar manner resulted in deposition of more solid.

Yield, 1·2 g. (60%). Purity, 99·8% m.p. 92-93° (Lit.[37], 94°). (Found: C, 74·40; H, 3·91. $C_{18}H_{10}O_4$ requires C, 74·48; H, 3·47%). i.r. ($CHCl_3$) 2225 (s) (C≡C); 1760 (s) cm^{-1} (C=O)

The melting point cited is that of Muramoto[37] et al. published in a communication with appeared after the completion of this work.

In view of the good yield and purity of the product, this method was employed in all subsequent peroxide preparations. However, owing to the hazardous nature of the product, preparations were not undertaken where the total yield of peroxide would exceed 5 g.

2.4. Peroxide estimation

The peroxide purity was estimated by iodometric titration.[38] The method outlined below was also used for the analysis of the kinetic experiments.

The peroxide (ca., 0·05 moles, weighed accurately) was dissolved in chloroform (25 ml.) in a 250 ml. conical flask. The flask was flushed with dry nitrogen for 30 secs., and a solution (20 ml.) of 0·0005% ferric chloride hexahydrate in glacial acetic acid and solid potassium iodide (ca., 4 g.) were added. The flask was swirled gently, stoppered and placed in the dark for 40-45 mins. Water (ca. 100 ml.) was then added. The flask was swirled to dissolve all the potassium iodide and the liberated iodine was titrated with 0·01N sodium thiosulphate solution to starch end point. The colour change was brown to colourless.

It should be stressed that the above procedure applies for solutions containing approximately 0·05 moles of peroxide. The reaction period in the dark (namely 45 mins.,) was found to be necessary after shorter periods (e.g. 10 mins.) had resulted in inconsistent titres, suggesting incomplete reaction with the potassium iodide. Weights of peroxide in excess of this figure require a longer reaction time in contact with the potassium iodide.

2.5. The synthesis of p-substituted phenylpropiolyl peroxides

2.5.1. p-chloro-, p-bromo-, and p-methylphenylpropiolyl peroxides

p-Chlorocinnamic acid (83% yield; m.p. 240°; Lit.*, 240-242°) was prepared by the method of Koo[39] et al., from malonic acid (100 g. 0·96 moles) and p-chlorobenzaldehyde (67 g. 0·48 moles) in pyridine (200 ml.) with piperidine (7 ml.).

The acid (72 g. 0·39 moles) was esterified by boiling for 6 hrs., with ethanol (300 ml.) containing concentrated sulphuric acid (20 ml.). The product was extracted into ether which was washed with water and dried. On evaporation of the solvent the ester separated as a colourless oil which was taken up in cold carbon tetrachloride and treated with bromine as described for the parent ester. The yield of crude ethyl-α,β-dibromo-β-p-chlorophenylpropionate was 84%.

The crude material (124 g. 0·33 moles) was dehydrobrominated in ethanol (600 ml.) and potassium hydroxide (84 g. 1·5 moles), yielding p-chlorophenylpropiolic acid (80%; m.p. 192-3°. Lit.[40], 193-5°).

p-Chlorophenylpropiolyl peroxide was prepared from the acid in 50% yield and 99% purity by the method described above for the parent peroxide, with the exception that the acid was introduced as an ice cold solution in ether. m.p. 109°. i.r. ($CHCl_3$); 2250 (s) (C≡C); 1750 (s) $cm.^{-1}$ (C=O).

p-Bromophenylpropiolyl peroxide (Yield 40%; m.p. 123°; i.r. ($CHCl_3$); 2250 (s) (C≡C); 1750 (s) $cm.^{-1}$ (C=O)) and p-methylphenylpropiolyl peroxide (Yield 50%; m.p. 109°; i.r. ($CHCl_3$); 2250 (s) (C≡C); 1750 (s) $cm.^{-1}$ (C=O) were prepared similarly.

2.5.2. p-methoxyphenylpropiolyl peroxide

Some difficulty was encountered in the preparation of p-methoxyphenylpropiolic acid.

The attempted preparation and dehydrobromination of ethyl-α, β-dibromo-β-p-methoxyphenyl propionate resulted in formation of an impure oil with weak $\nu_{max.}$ 2250 $cm.^{-1}$ suggesting little if any acetylenic nature. This supports the observation[41] that α,β-dibromo-β-methoxyphenylpropionic acid gives poor ester formation in ethanol and concentrated sulphuric acid.

Moreover, treatment of p-methoxycinnamic acid (60 g. 0·34 moles) in boiling carbon tetrachloride (1·2 l.) with bromine (55 g. 0·34 moles) and dehydrobromination of the resulting dibromo acid (m.p. 150°) with (i) ethanolic potassium hydroxide and (ii) lithium chloride in dimethylformamide gave unexpected products.

(i) α,β-dibromo-p-methoxyphenylpropionic acid (104 g. 0·31 moles) was boiled for 24 hrs., in ethanol (500 ml.) containing potassium hydroxide (78 g. 1·4 moles). The bulk of the ethanol was distilled off and the residue poured into ice-water (500 ml.). The organic material was liberated by acidification with hydrochloric acid (Sp. Gr. 1·18) and extracted into ether (3 x 200 ml.). The extract was washed with water (3 x 100 ml.), dried, and the solvent removed under reduced pressure to yield a white solid, p-methoxy-β-bromostyrene. 75% yield; i.r. (nujol); 3050 (m); 960 (s) (<u>trans</u> substituted C=C); 1610 (s) $cm.^{-1}$ (Ph conjugated with C=C). n.m.r. ($CDCl_3$) τ ; 6·20 (s. OMe); 2·3-3·6 (m. Ph and olefinic H). m.p. 48-50° (Lit.*, 50°).

(ii) The dibromo acid (5 g. 0·02 moles) was dissolved in the minimum quantity of dimethylformamide and lithium chloride (2·6 g. 0·06 moles) added. The mixture was heated under nitrogen on a boiling water bath for 4 hrs. The solvent was removed on a rotary evaporator and the residuel oil dissolved in aqueous sodium bicarbonate solution. Acidification with concentrated hydrochloric acid yielded a white solid which was filtered off and dried in the oven at 60°.

The product was identified as trans-β-bromo-4-methoxycinnamic acid (78% yield). m.p. 138° (Lit.*, 139°) i.r. (nujol); 1790 (s) (acid carbonyl); 1630 (m) cm.$^{-1}$ (C=C). n.m.r. (TFA.) τ 6·0 (s. OMe); multiplet in aromatic and olefinic region and acid proton downfield.

In view of the above, attention was turned to the preparation using the methyl ester. This was prepared from p-methoxy-cinnamic acid (110 g. 0·62 moles) suspended in anhydrous methanol (1·8 l.) by bubbling anhydrous hydrogen chloride gas through the suspension, for approximately 20 mins.

The mixture was refluxed for 4 hrs. during which time complete solution took place. Approximately 1 l. of methanol was distilled off and the residue cooled. White needles were deposited and collected by filtration. Yield 99%.

The ester (80 g. 0·42 moles) was treated with bromine (80 g. 0·5 moles) in cold carbon tetrachloride (400 ml.) and the resulting dibromo compound (120 g. 0·06 m) dehydrobrominated in ethanol (100 ml.) containing potassium hydroxide (15 g. 0·27 moles). The yield was 31%; m.p. 142-3° (Lit.*, 143°).

The peroxide was prepared from the acid as described before for the p-chloro-compound. Yield 50%; m.p. 75°. i.r. ($CHCl_3$); 2250 (s) (C≡C); 1760 (s) cm.$^{-1}$ (C=O).

2.6. Gas-liquid chromatography

2.6.1. Preparation and purification of materials

Phenylacetylene had b.p. 142-3° (Lit.*, 142-4°).

Diphenylacetylene, tolan, was recrystallised from ethanol. m.p. 62°. (Lit.*, 62·5°).

Biphenyl was recrystallised from light petroleum (boiling range 40-60°) and had m.p. 71°. (Lit.*, 71°).

α-methylstyrene had b.p. 167-169° (Lit.*, 167-170°).

α-4-dimethylstyrene, b.p. 69°/10 m.m. (Lit.*, 184-5°), was supplied by Dr. I.H. Sadler.

Hexachloroethane was recrystallised from ethanol/ether and had m.p. 185-6°. (Lit.*, 186-7).

Bicumyl (85% yield) was prepared by the decomposition of benzoyl peroxide (2 g. 0·008 moles) in cumene (75ml.) at 110° for 4 hrs. and recrystallised from light petroleum to give colourless needles m.p. 120°. (Lit.*, 120°).

1,4-diphenylbuta-1,3-diyne was prepared by the method of Campbell and Eglinton[42] from phenylacetylene (2 g. 0·02 moles), cupric acetate (5·5 g. 0·027 moles), pyridine (10 ml.) and methanol (10 ml.). Yield 60%. It was recrystallised from ethanol and had m.p. 87°. (Lit.[42], 87-88°).

1,3-diphenylpropyne was prepared according to the method of Jacobs and Dankner[43] by adding phenylacetylene (45 g. 0·44 mole) in dry ether (50 ml.) dropwise to a stirred ethereal solution of methylmagnesium bromide (0·5 mole) and refluxing the mixture for 1 hr. Cuprous chloride (0·4 g.) and cupric chloride (0·4 g.) were added and the mixture refluxed for a further 30 min. Benzyl bromide (70 g. 50 ml. 0·44 mole) in ether (50 ml.) was added dropwise to the stirred solution and refluxed for 46 hr. After cooling in ice, cold aqueous hydrochloric acid was added cautiously and the organic material extracted with ether. The extract was washed with water, aqueous sodium bicarbonate, water, dried and distilled. Yield; 31 g. 40%. b.p. 155-160°/5 m.m. (Lit.[43] 140-145°/3 m.m.).

Diazomethane in ethereal solution was prepared from p-tolylsulphonylmethylnitrosamide (2·14 g. 0·01 mole) in ether (30 ml.) and potassium hydroxide (0·4 g. 0·007 mole) in ethanol (10 ml.). The diazomethane was distilled out of the mixture as an azeotrope with ether using a water bath. The ethereal solution was stored at -20°.

2.6.2. Instrumentation

All the quantitative and the bulk of the qualitative gas-liquid chromatographic analyses were carried out on a Griffin D6 chromatograph employing a gas density balance detector. Peak areas were calculated with a "Kent chromalog" integrator.

Some qualitative analyses were performed using a Perkin-Elmer F11 gas-chromatograph with a flame ionisation detector.

The gas density balance has the advantage that the only property of the sample governing the detector response is its molecular weight. The peak area (A) corresponding to any given compound can be directly related to the number (n) of moles by equation (i).[44]

$$n = \frac{kA}{(M-m)} \quad \ldots\ldots\ldots\ldots\ldots \quad \text{(i)}$$

where m = molecular weight of carrier gas; M = molecular weight of compound eluted and k = a constant depending on apparatus construction and operating conditions.

Thus, for a single injection of a mixture of compounds:

$$\frac{n_i}{n_s} = \frac{A_i\,(M_s-m)}{A_s\,(M_i-m)} \quad \ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

where subscript (s) refers to an added internal standard and subscript (i) to the i^{th} component. Thus, the composition of the mixture can be calculated directly from the peak-area ratio A_i/A_s and detector calibration is therefore unnecessary. This formula is independent of sample size and operating conditions.

The composition of a given mixture was determined by gas-liquid chromatography after the addition of a known weight of an internal standard and the application of equation (ii). In all cases the peak-area ratio was taken as the mean of three determinations.

2.6.3. Measurement of retention times

Instrument: Griffin D6.

Column: 5% Neopentyl glycol succinate on 80/100 mesh acid washed and silanized Chromosorb P. Length, 2 m.

Nitrogen inlet pressure: 15 lb./□".

Relative retention times at 80°.

Cumene	0·24	α-methylstyrene	0·58
Phenylacetylene	0·42	Hexachloroethane	0·68
α,4-dimethylstyrene	1·00 (20·1 min.)		

Relative retention times at 180°

Methyl phenyl propiolate	1·3	bicumyl	2·4
biphenyl	1·0 (6·5 min.)	tolan	2·7
bibenzyl	2·4	1,3-diphenylpropyne	6·7

Instrument: Perkin-Elmer F11.

Column: 1½% Silicone gum on 80/100 mesh Chromosorb W.

length, 2m.

Nitrogen inlet pressure: 30 lb./□".

Temperature 200°.

Retention time of diphenyl diacetylene: 3·0 mins.

2.7. The products of the decomposition of phenylpropiolyl peroxide in various solvents

The reactions were carried out in apparatus under nitrogen. A solution of the peroxide (2 g. 6·9 m.moles) in the solvent (100 ml.) under investigation was placed in a flask surrounded by an outer vessel containing methanol (b.p. 65°). On refluxing the methanol, a uniform reaction temperature of 65° was achieved. The reaction flask was connected to a gas burette which constituted one arm of a manometer, thus, enabling measurement of any gaseous products. The levels of water in the two arms of the manometer were equilibrated before reading the initial and final volumes. The water in the gas burette was surmounted by 5 ml. of silicone oil to prevent carbon dioxide absorption by the water. The final volume was read once the apparatus had cooled to room temperature.

On cooling, the reaction mixture was transferred to a 250 ml. standard flask and made up to the mark with ether. 2 x 5 ml. samples were withdrawn by pipette and used for gas-liquid chromatographic analysis (See Tables III and IV below). The remainder was transferred to a separating funnel and any acid formed in the decomposition was extracted with aqueous sodium hydroxide solution in the usual manner. (See Table III).

The ether layer was washed with water and dried. Evaporation of the ether on the rotary evaporator left an organic residue which was treated differently according to the solvent being studied, as described below.

Table III. Production of phenylpropiolic acid and carbon dioxide during decomposition of phenylpropiolyl peroxide

Solvent	Phenylpropiolyl peroxide		Phenylpropiolic acid			Carbon dioxide	
	g.	m.moles	g.	%	m.moles	ml.*	m.moles
Cumene	2·00	6·9	1·27	64	8·70	0	0·00
Chloroform	2·32	7·9	0·80	35	5·48	80	3·57
Toluene	2·36	8·1	1·02	42	6·99	42	1·88
Benzene	2·20	7·6	0·45	20	3·08	46	2·06
Carbon Tet.	2·50	8·6	0·00	0	0·00	81	3·61

* Volume corrected to N.T.P.

Table IV. Production of phenylpropiolic acid estimated by g.l.c. analysis*

Solvent	Peroxide m.moles	Biphenyl m.moles	Aester/ APhPh	Acid m.moles	Acid %
Cumene	0·1380	0·1545	1·219	0·1795	65
Chloroform	0·1599	0·1299	0·625	0·0774	24
Toluene	0·1675	0·1307	1·090	0·1359	42
Benzene	0·1569	0·1583	0·410	0·0619	20
Carbon Tet.	0·1725	0·1620	0·000	0·0000	0

*A known weight of biphenyl was added to each tube to act as an internal standard. The contents were treated with an ethereal solution of diazomethane to convert the acid to its methyl ester.

Examination of the organic residues

Table V summarises the products present by gas-liquid chromatographic analysis either of the bulk organic residue or of the sample removed for this purpose.

Table V. G.l.c. examination of products

	Cu	Ch	To	Be	C.Tet.
Phenyl acetylene	A	A	<0·04	A	A
tolan	-	-	-	A	-
diphenyl diacetylene	A	A	A	A	A
bicumyl	A	-	-	-	-
bibenzyl	-	-	<0·04	-	-
biphenyl	-	-	-	A	-
hexachloroethane	-	<0·07	-	-	<0·07
1,3-diphenylpropyne	-	-	0·27	-	-

Abbreviations: Cu: cumene; Ch: chloroform; To: toluene; Be: benzene; C.Tet: carbon tetrachloride.

A: Compound absent from reaction mixture

-: Compound not expected (nor found) in reaction mixture.

The figures are expressed as mole per mole starting material.

The residue from the reaction in cumene was examined in the most detail. Gas-liquid chromatographic analysis of the 5 ml. sample indicated the presence of α-methyl styrene. This was verified by an independent experiment, performed on a small scale. The α-methyl styrene was estimated using α,4-dimethylstyrene as internal standard, and was found to be 0·01 mole/mole peroxide.

All the solvents were removed from the residue in vacuo. (0·1 m.m. for 6 hrs.). The resulting viscous solid was examined by i.r. and n.m.r. spectroscopy, i.r. ($CHCl_3$); 2250 (s) (C≡C);

1750 (m) 1710 (s) $cm.^{-1}$ (C=O). n.m.r. ($CDCl_3$) τ 2·80 (d). (Phenyl protons); 8·10 (s); 8·80 (d) (aliphatic protons)

The spectroscopic evidence suggested that the compound was impure cumyl phenylpropiolate as did the hydrolysis of a sample (0·2 g.) with dilute aqueous sodium hydroxide. The i.r. spectrum ($CHCl_3$) of the acidic component confirmed it was phenylpropiolic acid. The spectrum of the alcoholic component contained no acetylenic function.

The column chromatography of the residue from a second experiment resulted in hydrolysis of the product. On silica gel, eluting with petroleum (b.p. 40-60°) which contained a progressively increasing proportion of ether, phenylpropiolic acid was obtained in *ca.*, 50% yield.

The residues from the other reactions consisted of tars which were not separable by column chromatography as this, both on silica gel and neutral alumina, caused hydrolysis and retention of the products on the column.

2.8. The kinetics of the decomposition of phenylpropiolyl peroxide in various solvents

2.8.1. Introduction

The kinetic runs were carried out by the following procedure. A stock solution of the peroxide of known concentration was prepared. Aliquots of this were transferred by pipette to a series of glass tubes which had been flushed with nitrogen. (The tube dimensions were: length, 15 cm., internal diameter, 7 m.m.).

The tubes were gently flushed once more with nitrogen, sealed and placed in a thermostatically controlled oil bath. The tubes were removed at regular intervals and plunged into a chloroform bath at 0° to terminate the reaction. The contents were quantitatively transferred, by rinsing with chloroform, to a 250 ml. conical flask and the peroxide content of each determined by iodometric titration as described previously.

The initial concentration at zero time (to) was determined, for each run, by the estimation of the peroxide concentration in an aliquot of the original solution.

2.8.2. Preliminary experiment in cumene

0·5552 g. (1·918 m.moles) of peroxide was dissolved in cumene (50 ml.). 1 ml. aliquots were used.

$$Co = 0{\cdot}0355 \text{ moles. litre}^{-1}$$

Table VI. Decomposition of phenylpropiolyl peroxide in cumene at 50°

Hours	ml.	ml.	ave.ml.	%	$C \times 10^2$	Co/C	$\ln {}^{Co}/_{C}$
0	7·12	7·09	7·10	100·0	3·55	1·000	0·000
0·5	6·26	6·15	6·20	87·5	3·10	1·145	0·135
1	5·79	5·75	5·77	81·1	2·88	1·265	0·236
1·5	4·86	4·80	4·83	68·0	2·42	1·464	0·384
2	4·25	4·30	4·28	63·1	2·24	1·588	0·463
2·5	3·79	3·75	3·77	52·4	1·86	1·910	0·647
3	3·39	3·35	3·37	47·5	1·68	1·995	0·691
3·5	3·19	3·21	3·20	45·0	1·59	2·238	0·806

Key to Tables: VI - VIII.

ml.: Volume of 0·01N sodium thiosulphate solution

Co: Peroxide concentration in moles.litre^{-1} at t_o

C: Peroxide concentration in moles.litre^{-1} at time t.

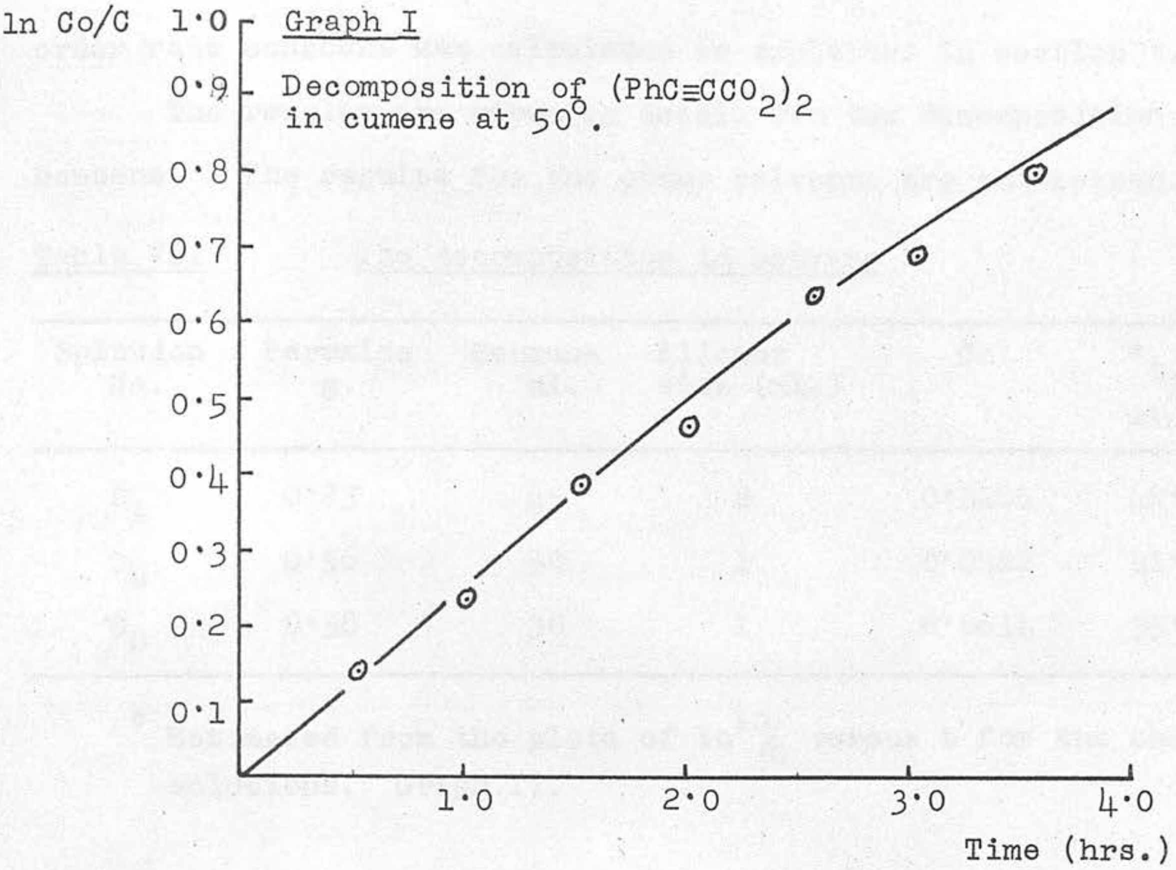
%: Percentage peroxide remaining at time t.

Graph No.I indicates that the peroxide has a half-life ($t_{\frac{1}{2}}$) of 2·8 hrs. at 50° and also that approximately first-order kinetics are being followed. It was considered that a higher temperature and correspondingly shorter half-life would give more useful results.

2.8.3. Kinetic studies in solutions of varying concentration at 65°

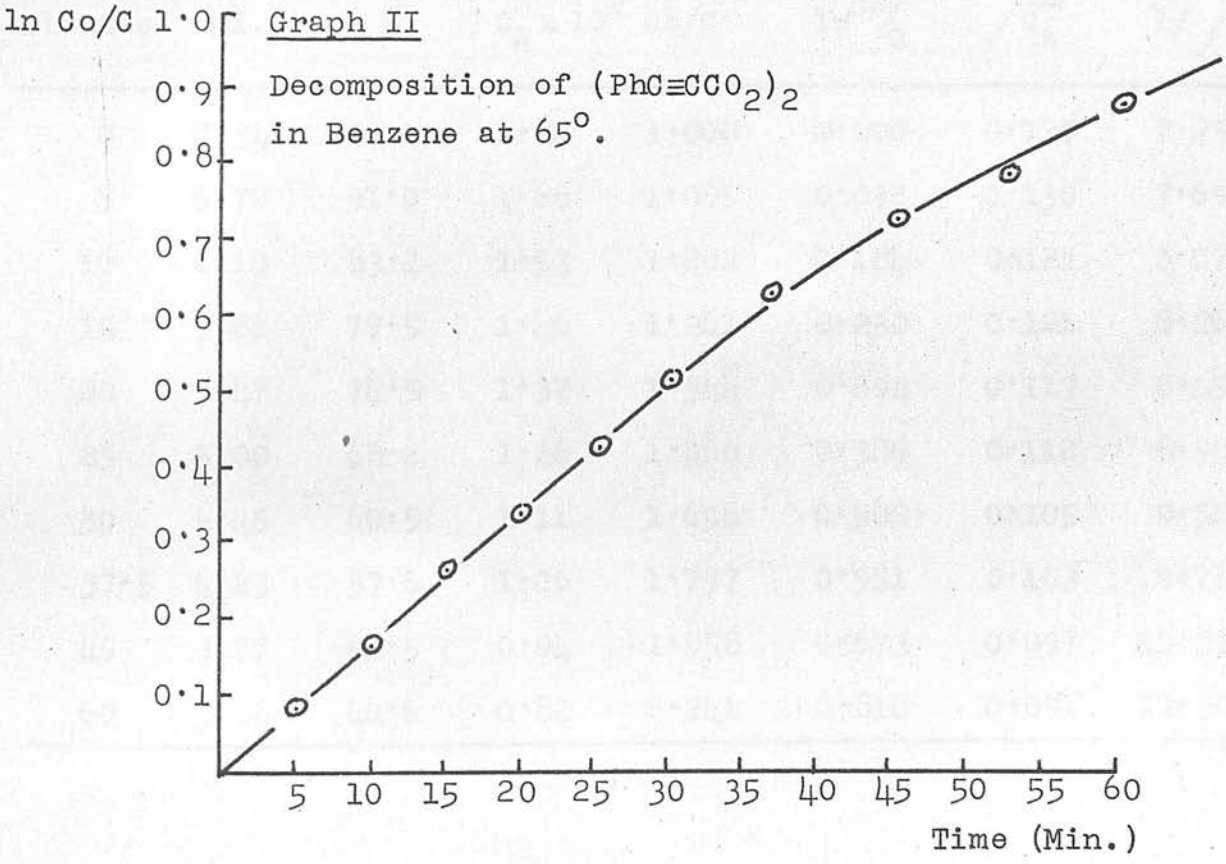
The decomposition of phenylpropiolyl peroxide in the five solvents studied in section 3.7 was reinvestigated in order to elucidate the kinetics, particularly any induced decomposition. For each solvent, three solutions of different initial peroxide concentration were used and labelled C_A, C_B and C_C in order of increasing peroxide concentration. A plot of $\ln {}^{Co}/C$ against t was constructed for each solution in the usual manner.

In addition, from the plots of $1/\sqrt{C_A}$ vs. $1/\sqrt{C_B}$; $1/\sqrt{C_B}$ vs. $1/\sqrt{C_C}$ and $1/\sqrt{C_A}$ vs. $1/\sqrt{C_C}$, the constant a in equation (viii) in section 3.3 was deduced. Using this value for a, a plot of $\ln [(a + \sqrt{C})/\sqrt{C}]$ versus t was constructed for each value of C (viz., C_A, C_B and C_C). Where possible, an estimate of the first-



Graph I

Decomposition of $(PhC\equiv CCO_2)_2$ in cumene at 50°.



Graph II

Decomposition of $(PhC\equiv CCO_2)_2$ in Benzene at 65°.

order rate constant was calculated as explained in section 3.3.

The results are given in detail for the decomposition in benzene. The results for the other solvents are summarised.

Table VII The decomposition in benzene

Solution No.	Peroxide g.	Benzene ml.	Aliquot size (ml.)	Co	*$t_{\frac{1}{2}}$ min.
C_A	0·23	45	2	0·0184	46·5
C_B	0·56	50	1	0·0362	41·0
C_C	0·58	30	1	0·0614	35·0

* Estimated from the plots of $\ln {}^{10}/_{C}$ versus t for the three solutions. Graph II.

Solution A

Minutes	ml.	%	$C_A \times 10^2$	Co/C	$\ln {}^{Co}/_{C}$	$\sqrt{C_A}$	$1/\sqrt{C_A}$
0	7·34	100·0	1·84	1·000	0·000	0·137	7·29
5	6·70	91·0	1·68	1·095	0·092	0·130	7·69
10	6·10	83·2	1·53	1·202	0·184	0·124	8·07
15	5·82	79·5	1·46	1·261	0·230	0·121	8·26
20	5·47	74·5	1·37	1·344	0·294	0·117	8·55
25	5·00	68·2	1·26	1·460	0·380	0·112	8·93
30	4·45	60·5	1·11	1·658	0·505	0·105	9·52
37·5	4·23	57·6	1·06	1·737	0·551	0·103	9·71
45	3·77	51·5	0·94	1·958	0·673	0·097	10·31
60	3·28	44·6	0·82	2·241	0·810	0·091	10·99

Solution B

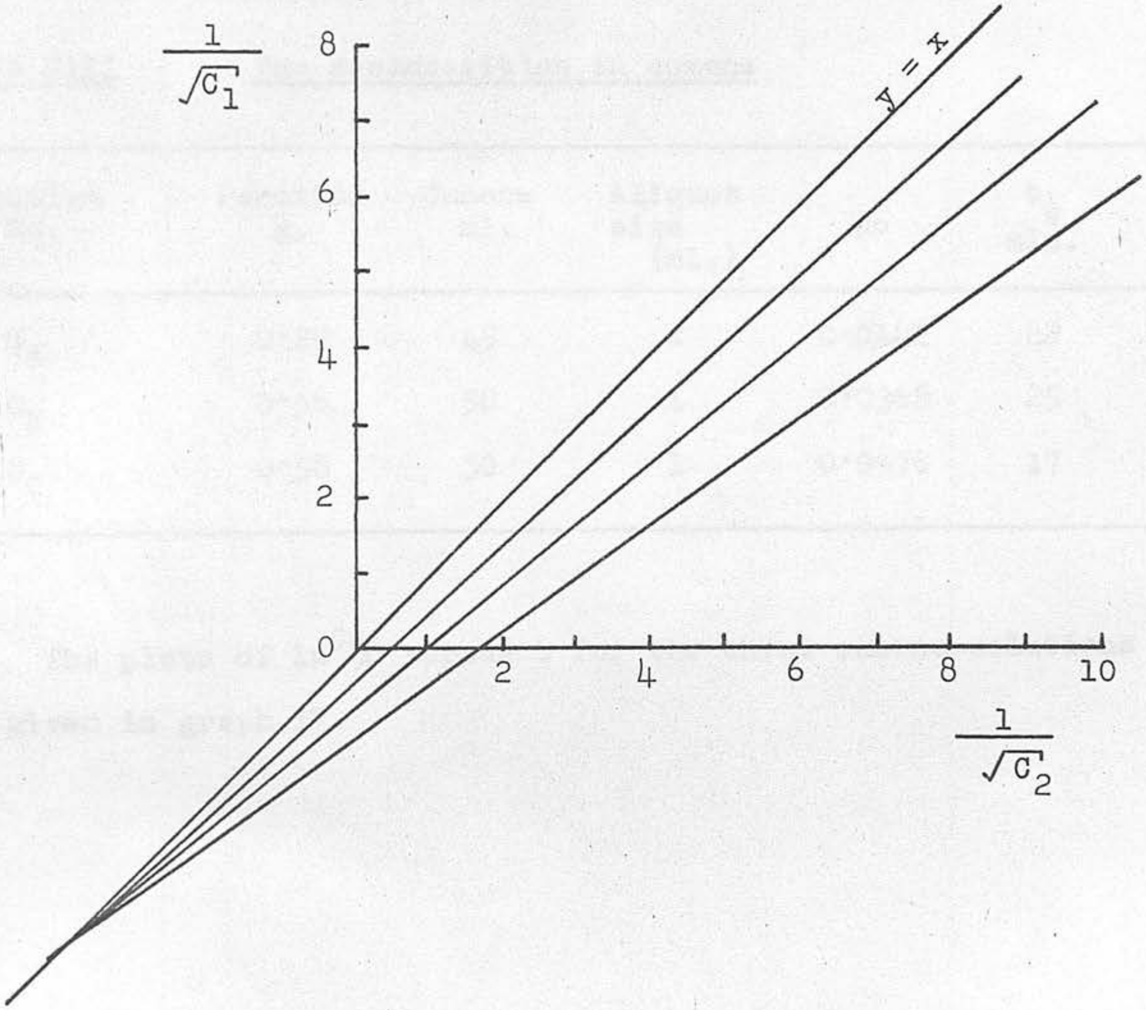
Minutes	ml.	%	$C_B x10^2$	Co/C	$\ln {}^{Co}/_{C}$	$\sqrt{C_B}$	$1/\sqrt{C_B}$
0	7·22	100·0	3·62	1·000	0·000	0·193	5·18
5	6·68	92·4	3·34	1·082	0·081	0·183	5·46
10	6·11	84·5	3·06	1·182	0·167	0·175	5·71
15	5·56	76·8	2·78	1·302	0·265	0·167	5·99
20	5·15	71·2	2·57	1·408	0·341	0·160	6·25
25	4·73	65·4	2·36	1·538	0·428	0·154	6·49
30	4·32	59·8	2·16	1·678	0·516	0·147	6·80
37·5	3·85	53·2	1·93	1·875	0·629	0·139	7·19
45	3·57	48·6	1·76	2·059	0·723	0·133	7·52
60	3·13	43·2	1·49	2·430	0·890	0·122	8·19

Solution C

Minutes	ml.	%	$C_C x10^2$	Co/C	$\ln {}^{Co}/_{C}$	$\sqrt{C_C}$	$1/\sqrt{C_C}$
0	12·23	100·0	6·14	1·000	0·000	0·248	4·03
5	10·73	87·7	5·38	1·141	0·132	0·232	4·31
10	9·65	78·5	4·83	1·272	0·242	0·219	4·56
15	9·00	73·5	4·51	1·361	0·314	0·212	4·72
20	8·21	66·9	4·11	1·494	0·401	0·203	4·93
25	7·33	60·1	3·69	1·665	0·508	0·192	5·21
30	6·93	56·6	3·47	1·770	0·571	0·186	5·38
37·5	6·12	50·5	3·10	1·980	0·681	0·176	5·68
45	5·56	45·3	2·79	2·200	0·787	0·167	5·99
60	4·51	36·5	2·24	2·738	1·008	0·150	6·67

Graph III

Plot of $\frac{1}{\sqrt{C_1}}$ vs. $\frac{1}{\sqrt{C_2}}$ for the decomposition of $(PhC{\equiv}CCO_2)_2$ in Benzene at 65°.



The plots of $1/\sqrt{C_1}$ versus $1/\sqrt{C_2}$ for benzene are given in graph III and these can be taken as representative of the rest (except cumene). As discussed in section 3.3, the slope (m) and intercept (c) of the best straight line through these points was calculated by the method of least squares on a KDF9 computer using a programme supplied by Dr. Lowe of this department. From the point of coincidence of each of the three lines with the line $1/\sqrt{P_1} = 1/\sqrt{P_2}$ the constant a was calculated.

The results for cumene are given in table VIII, and those for chloroform, toluene and carbon tetrachloride in table IX.

Table VIII The decomposition in cumene

Solution No.	Peroxide g.	Cumene ml.	Aliquot size (ml.)	Co	$t_{\frac{1}{2}}$ min.
C_A	0·20	45	2	0·0141	42
C_B	0·56	50	1	0·0368	25
C_C	0·58	30	1	0·0576	17

The plots of $\ln {}^{Co}/_{C}$ versus t for the three cumene solutions are given in graph IV.

Table VIII (Contd.)

Minutes	0	5	10	15	20	25	30	40	50	60
$C_A \times 10^2$	1·41	1·31	1·18	1·04	0·99	0·91	0·86	0·70	0·64	0·61
lnCo/C	0·000	0·100	0·183	0·260	0·358	0·434	0·447	0·646	0·790	0·846
$\sqrt{C_A}$	0·119	0·115	0·109	0·104	0·099	0·095	0·093	0·084	0·080	0·078
$1/\sqrt{C_A}$	8·48	8·69	9·23	9·62	10·05	10·48	10·79	11·95	12·50	12·80
$C_B \times 10^2$	3·68	3·29	2·81	2·38	2·10	1·75	1·59	1·42	1·20	1·04
ln Co/C	0·000	0·111	0·262	0·435	0·561	0·744	0·841	0·949	1·121	1·262
$\sqrt{C_B}$	0·192	0·181	0·168	0·154	0·145	0·132	0·126	0·119	0·109	0·102
$1/\sqrt{C_B}$	5·21	5·53	5·95	6·49	6·89	5·58	7·94	8·40	9·17	9·80
$C_C \times 10^2$	5·76	4·62	3·82	2·96	2·49	1·99	1·89	1·39	1·14	0·94
ln Co/C	0·000	0·221	0·410	0·666	0·837	1·061	1·112	1·421	1·620	1·816
$\sqrt{C_C}$	0·240	0·214	0·195	0·172	0·158	0·141	0·138	0·118	0·107	0·097
$1/\sqrt{C_C}$	4·17	4·65	5·13	5·81	6·33	7·09	7·25	8·48	9·35	10·31

Graph IV

Decomposition of $(PhC\equiv CCO_2)_2$ in Cumene at 65°

⊙ = C_A; ⊡ = C_B; △ = C_C

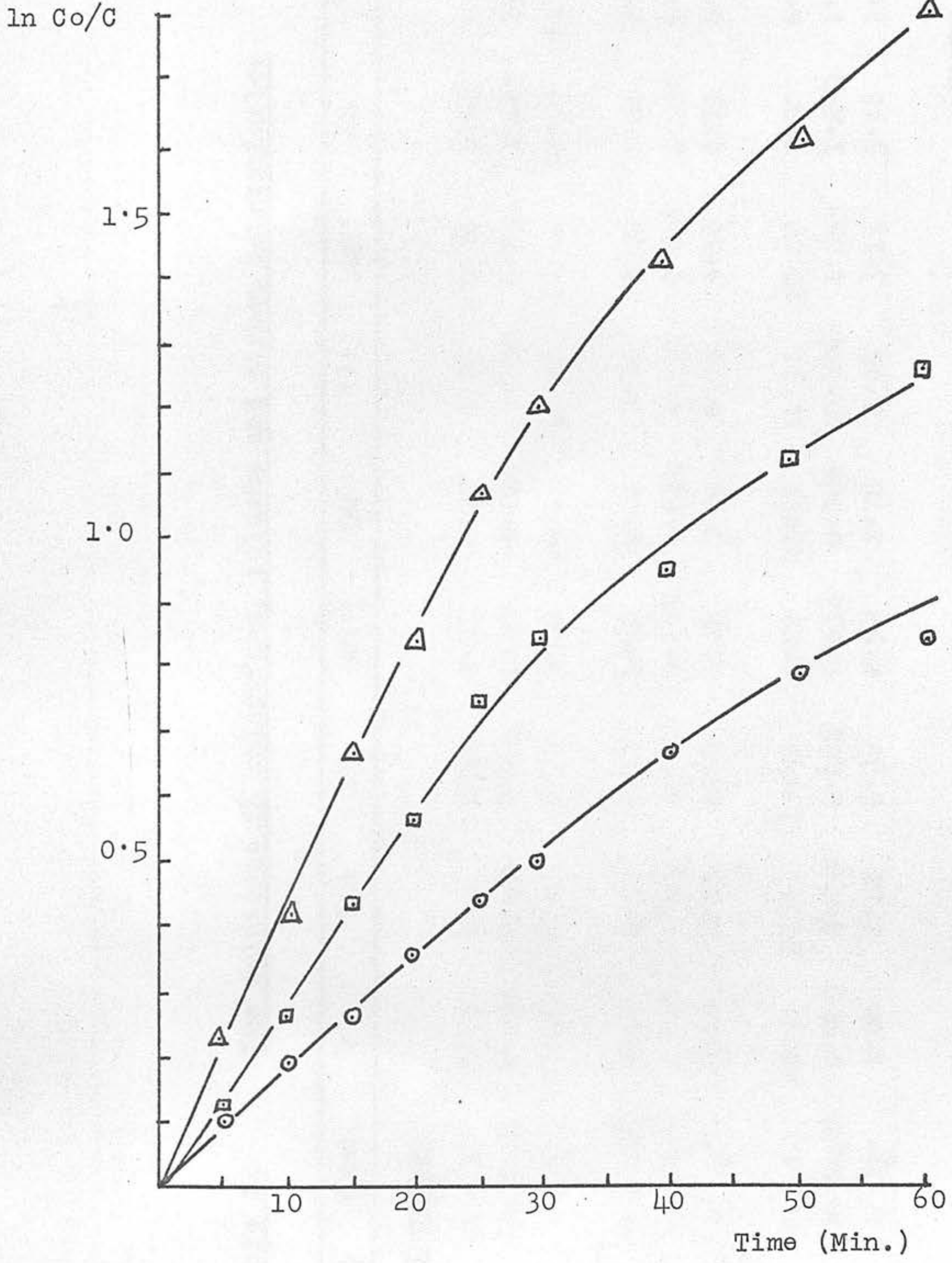


Table IX   The solutions in chloroform, toluene and carbon tetrachloride

No.	Mins.	0	7·5	15	22·5	30	37·5	45	60	75	90
Chloroform											
	$C \times 10^2$	1·79	1·52	1·32	1·13	0·97	0·85	0·76	0·58	0·46	0·32
A	$\ln Co/C$	0·000	0·166	0·304	0·466	0·616	0·750	0·855	1·125	1·365	1·418
	$1/\sqrt{C}$	7·46	8·13	8·69	9·43	10·15	10·88	11·44	13·09	14·77	15·97
	$C \times 10^2$	7·38	6·14	5·20	4·48	4·00	3·50	3·10	2·56	2·08	1·71
B	$\ln Co/C$	0·000	0·182	0·350	0·498	0·614	0·745	0·866	1·056	1·268	1·465
	$1/\sqrt{C}$	3·68	4·03	4·39	4·72	5·00	6·35	5·68	6·25	6·94	7·63
	$C \times 10^2$	28·70	22·20	17·92	15·22	13·03	11·31	10·02	7·90	6·72	5·67
C	$\ln Co/C$	0·000	0·257	0·469	0·632	0·788	0·926	1·053	1·290	1·450	1·620
	$1/\sqrt{C}$	1·86	2·12	2·36	2·57	2·78	2·98	3·14	3·56	3·86	4·20

[Contd.]

Table IX [Contd.]

No.	Mins	0	7·5	15	22·5	30	37·5	45	60	75	90
Toluene											
A	C x 10^2	3·59	3·37	2·88	2·52	2·22	1·98	1·76	1·46	1·20	1·02
	ln Co/C	0·000	0·104	0·218	0·354	0·481	0·594	0·714	0·898	1·100	1·275
	1/ $\sqrt{C}$	5·29	5·58	5·92	6·29	6·71	7·09	7·52	8·26	9·17	9·90
B	C x 10^2	6·83	5·93	5·01	4·26	3·87	3·32	2·95	2·35	1·99	1·65
	ln Co/C	0·000	0·138	0·308	0·410	0·567	0·720	0·839	1·068	1·230	1·450
	1/ $\sqrt{C}$	3·83	4·10	4·46	4·61	5·08	5·49	5·81	5·54	7·09	7·75
C	C x 10^2	10·94	9·33	7·82	6·62	5·90	5·07	4·55	3·62	2·94	2·35
	ln Co/C	0·000	0·161	0·334	0·504	0·618	0·769	-·876	1·050	1·320	1·539
	1/ $\sqrt{C}$	3·03	3·27	3·58	3·89	4·12	4·44	4·69	5·10	5·81	6·54
Carbon Tetrachloride											
A	C x 10^2	2·02	1·87	1·66	1·51	1·37	1·25	1·19	0·99	0·91	0·84
	ln Co/C	0·000	0·078	0·194	0·290	0·388	0·479	0·530	0·709	0·792	0·876
	1/ $\sqrt{C}$	7·04	7·30	7·75	8·13	8·55	8·93	9·17	10·05	10·48	10·91
B	C x 10^2	3·36	3·00	2·68	2·40	2·18	1·97	1·80	1·52	1·34	1·19
	ln Co/C	0·000	0·113	0·233	0·336	0·434	0·535	0·624	0·794	0·920	1·039
	1/ $\sqrt{C}$	5·46	5·78	6·10	6·45	6·76	7·14	7·46	8·13	8·62	9·17
C	C x 10^2	6·69	5·74	4·86	4·31	3·92	3·46	3·16	2·62	2·18	1·91
	ln Co/C	0·000	0·157	0·321	0·438	0·531	0·659	0·749	0·936	1·120	1·252
	1/ $\sqrt{C}$	3·86	4·18	4·53	4·81	5·05	5·38	5·62	6·17	6·76	7·58

The half-lives in minutes for each solution in table IX are given below. These were obtained from the plots of $\ln {}^{C_o}/C$ versus t.

Chloroform			Toluene			Carbon Tet.		
A	B	C	A	B	C	A	B	C
34·0	34·0	24·8	44·8	36·0	33·2	58·2	50·5	41·4

Table X summarises the results for all the solutions except cumene, as in this case, the slopes of the plots of $^{1}/_{\sqrt{C_1}}$ versus $^{1}/_{\sqrt{C_2}}$ were greater than unity, giving a negative value for a as explained in section 3.3.

Table X. The slope (m) and intercept (c) of the best straight line through the points $^{1}/\sqrt{C_1}$ vs. $^{1}/\sqrt{C_2}$. Also, the corresponding value for the constant a.

Solution No.	m	(-c)	a
Benzene			
C v. B	1·181 ± 0·025	0·398 ± 0·134	0·455 ± 0·31
B v. A	1·206 ± 0·018	1·078 ± 0·123	0·192 ± 0·05
C v. A	1·427 ± 0·018	1·542 ± 0·096	0·277 ± 0·02
Toluene			
A v. B	0·845 ± 0·023	0·612 ± 0·169	0·253 ± 0·08
B v. C	0·847 ± 0·031	0·189 ± 0·174	0·810 ± 0·47
A v. C	0·718 ± 0·024	0·728 ± 0·174	0·388 ± 0·09
Carbon Tet.			
B v. C	0·094 ± 0·033	1·296 ± 0·238	0·045 ± 0·03
C v. A	1·107 ± 0·066	2·847 ± 0·364	0·038 ± 0·02
A v. B	0·939 ± 0·026	1·172 ± 0·228	0·052 ± 0·03
Chloroform			
A v. B	0·448 ± 0·009	0·435 ± 0·106	-1·269 ± 0·268
B v. C	0·593 ± 0·015	0·239 ± 0·085	1·701 ± 0·491
A v. C	0·266 ± 0·009	0·020 ± 0·109	-37·0 ± 32·0

The data for $\ln (a + \sqrt{C})/\sqrt{C}$ versus t is given for the value of a indicated for each of the solutions C_A, C_B and C_C for the solvents benzene, toluene, carbon tetrachloride and chloroform, in Table XI.

Table XI. The values of $\ln (a + \sqrt{C})/\sqrt{C}$

Benzene

a	0·192		0·192		0·277	
mins.	$\frac{a+\sqrt{C_A}}{\sqrt{C_A}}$	$\ln\frac{a+\sqrt{C_A}}{\sqrt{C_A}}$	$\frac{a+\sqrt{C_B}}{\sqrt{C_B}}$	$\ln\frac{a+\sqrt{C_B}}{\sqrt{C_B}}$	$\frac{a+\sqrt{C_C}}{\sqrt{C_C}}$	$\ln\frac{a+\sqrt{C_C}}{\sqrt{C_C}}$
0	2·498	0·884	1·996	0·691	2·115	0·747
5	2·480	0·907	2·048	0·716	2·194	0·784
10	2·548	0·936	2·098	0·741	2·268	0·818
15	2·585	0·948	2·150	0·764	2·315	0·838
20	2·642	0·971	2·200	0·786	2·418	0·878
25	2·715	0·996	2·241	0·809	2·442	0·894
30	2·821	1·036	2·305	0·834	2·488	0·912
37·5	2·862	1·052	2·380	0·865	2·570	0·944
45	2·980	1·092	2·442	0·894	2·660	0·978
60	3·105	1·132	2·564	0·942	2·850	1·048

Toluene

a	0·388		0·253		0·388	
mins.	$\frac{a+\sqrt{C_A}}{\sqrt{C_A}}$	$\ln\frac{a+\sqrt{C_A}}{\sqrt{C_A}}$	$\frac{a+\sqrt{C_B}}{\sqrt{C_B}}$	$\ln\frac{a+\sqrt{C_B}}{\sqrt{C_B}}$	$\frac{a+\sqrt{C_C}}{\sqrt{C_C}}$	$\ln\frac{a+\sqrt{C_C}}{\sqrt{C_C}}$
0	3·050	1·112	1·970	0·676	2·175	0·775
7·5	3·160	1·150	2·018	0·709	2·268	0·820
15	3·300	1·192	2·130	0·755	2·390	0·870
22·5	3·435	1·235	2·165	0·774	2·508	0·919
30	3·607	1·284	2·285	0·826	2·599	0·952
37·5	3·742	1·320	2·390	0·870	2·720	0·997
45	3·920	1·363	2·470	0·904	2·820	1·038
60	4·200	1·438	2·659	0·977	2·979	1·090
75	4·560	1·515	2·795	1·029	3·250	1·180
90	4·840	1·579	2·960	1·088	3·519	1·261

Carbon tetrachloride $a = 0·045$

Mins.	$\frac{a + \sqrt{C_A}}{\sqrt{C_A}}$	$\ln \frac{a + \sqrt{C_A}}{\sqrt{C_A}}$	$\frac{a + \sqrt{C_B}}{\sqrt{C_B}}$	$\ln \frac{a + \sqrt{C_B}}{\sqrt{C_B}}$	$\frac{a + \sqrt{C_C}}{\sqrt{C_C}}$	$\ln \frac{a + \sqrt{C_C}}{\sqrt{C_C}}$
0	1·318	0·274	1·245	0·218	1·172	0·160
7·5	1·326	0·281	1·260	0·230	1·188	0·171
15	1·349	0·299	1·272	0·241	1·206	0·185
22·5	1·364	0·310	1·291	0·256	1·219	0·195
30	1·382	0·323	1·306	0·267	1·225	0·203
37·5	1·400	0·336	1·320	0·276	1·241	0·266
45	1·410	0·344	1·338	0·290	1·252	0·226
60	1·445	0·368	1·368	0·312	1·279	0·244
75	1·465	0·381	1·389	0·327	1·306	0·266
90	1·496	0·401	1·412	0·345	1·341	0·294

Chloroform $a = 1·701$

mins.	$\frac{a + \sqrt{C_A}}{\sqrt{C_A}}$	$\ln \frac{a + \sqrt{C_A}}{\sqrt{C_A}}$	$\frac{a + \sqrt{C_B}}{\sqrt{C_B}}$	$\ln \frac{a + \sqrt{C_B}}{\sqrt{C_B}}$	$\frac{a + \sqrt{C_C}}{\sqrt{C_C}}$	$\ln \frac{a + \sqrt{C_C}}{\sqrt{C_C}}$
0	13·70	2·612	7·250	1·981	4·340	1·469
7·5	14·81	2·699	7·840	2·059	4·610	1·529
15	15·80	2·752	8·440	2·135	5·035	1·636
22·5	17·01	2·835	9·040	2·200	5·360	1·680
30	18·28	2·900	9·500	2·250	5·730	1·749
37·5	19·49	2·960	10·08	2·310	6·050	1·799
45	20·41	3·015	10·64	2·362	6·325	1·868
60	23·21	3·140	11·64	2·458	7·050	1·954
75	26·09	3·260	12·80	2·542	7·560	2·021
90	28·15	3·332	14·00	2·639	8·140	2·095

Graph number V illustrates the results for benzene. The slopes of these lines and the corresponding values of k are given in table XII. k was calculated (where possible) from the slopes as explained in section 3.3, equation (vii).

Graph V

$\ln \frac{a + \sqrt{C}}{\sqrt{C}}$ vs. t

Decomposition of $(PhC{\equiv}CCO_2)_2$ in benzene.

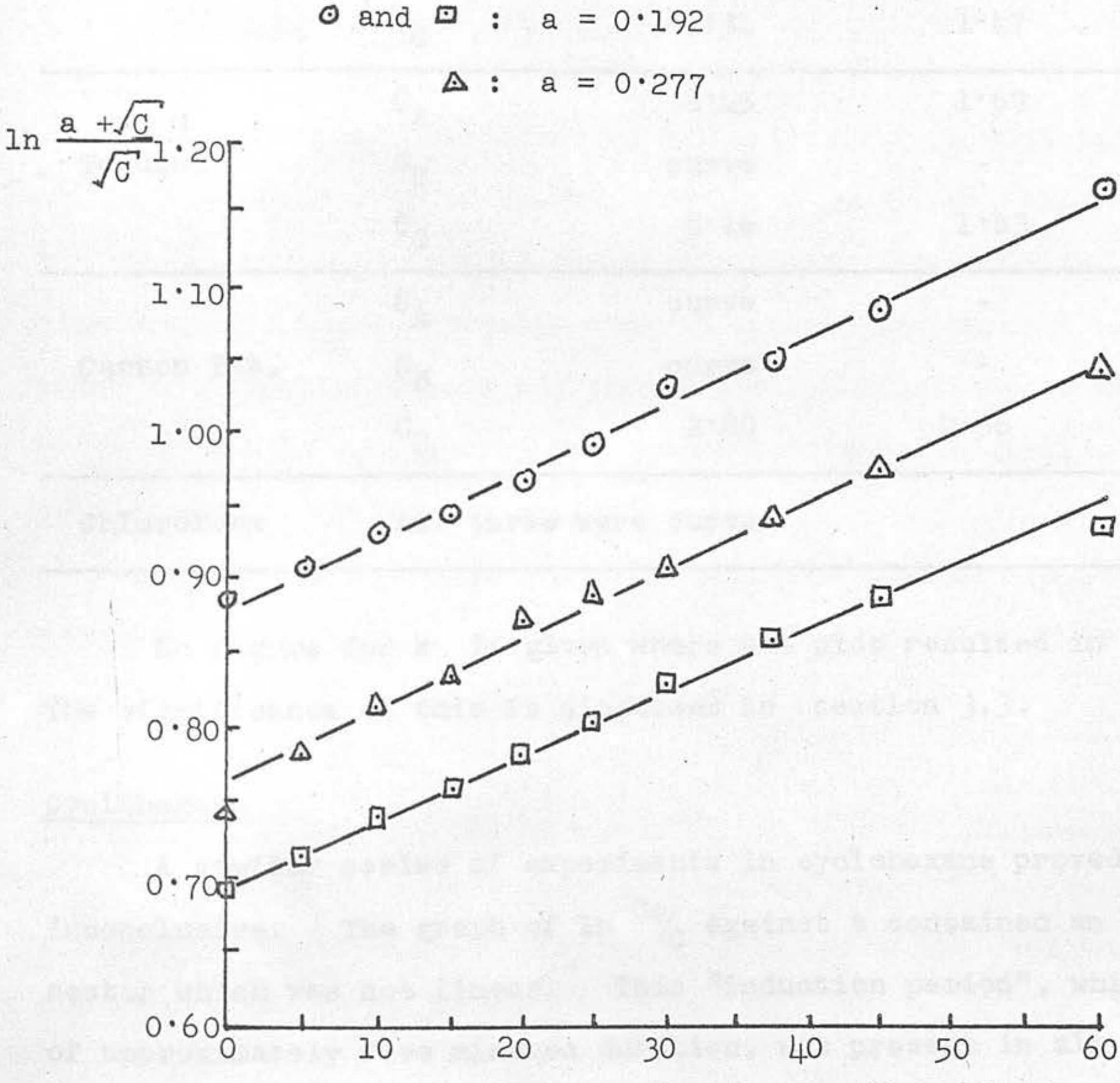


Table XII The slope (and corresponding value for k) of $\ln(a + \sqrt{C})/\sqrt{C}$ versus t.

Solvent	Curve	Slope x 10^5	k x 10^4
Benzene	C_A	7·59	1·52
	C_B	7·00	1·40
	C_C	7·34	1·47
Toluene	C_A	8·45	1·69
	C_B	curve	-
	C_C	8·16	1·63
Carbon Tet.	C_A	curve	-
	C_B	curve	-
	C_C	2·80	0·56
Chloroform	All three were curves		

No figure for k is given where the plot resulted in a curve. The significance of this is discussed in section 3.3.

Cyclohexane

A similar series of experiments in cyclohexane proved inconclusive. The graph of $\ln {}^{C_o}/_{C}$ against t contained an initial sector which was not linear. This "induction period", which was of approximately five minutes duration, was present in all the kinetic runs examined. The results for a typical run are given in the table overleaf.

mins.	0	5	10	15	20	25	30	35
C	0·0147	0·0147	0·0142	0·0088	0·0053	0·0041	0·0030	0·0020
ln Co/C	0·000	0·000	0·037	0·516	1·029	1·283	1·605	1·885

2.9. The kinetics of the decomposition of phenylpropiolyl peroxide in the presence of an inhibitor

Introduction

The decompositions detailed in section 2.8 gave linear plots for $\ln {}^{Co}/_{C}$ versus t up to approximately one half life, thereafter, the curves deviated from linearity suggesting the occurance of higher order kinetics arising from an induced decomposition. In order to investigate this and render the decomposition as near first-order as possible, experiments were undertaken with varying concentrations of added inhibitor.

In the kinetic experiments in sections 2.9 and 2.10,a peroxide concentration of 0·05M was used throughout and the reactions were run at 65·0° unless otherwise stated.

2.9.1. The decomposition in the presence of styrene inhibitor

Solutions in both dioxane and chloroform were investigated; the results for dioxane are summarised in table XIII and those for chloroform in table XIV.

Table XIII. Decomposition in dioxane + styrene inhibitor

I^*	Mins.	0	7·5	15	22·5	30	37·5	45	60
0	$Cx10^2$	5·11	2·42	1·53	1·15	0·95	-	-	-
	lnCo/C	0·000	0·747	1·208	1·495	1·684	-	-	-
0·2	$Cx10^2$	4·79	3·93	3·04	2·56	2·14	1·88	1·63	1·35
	lnCo/C	0·000	0·198	0·454	0·626	0·806	0·935	1·079	1·262

I^* = Molar concentration of inhibitor

The results are illustrated in graph VI. The increase in $t_{\frac{1}{2}}$ from 6·9 to 26·0 mins., on increasing the styrene concentration from zero to 0·2M indicates the effectiveness of its inhibitory powers.

Table XIV. Decomposition in chloroform + styrene inhibitor

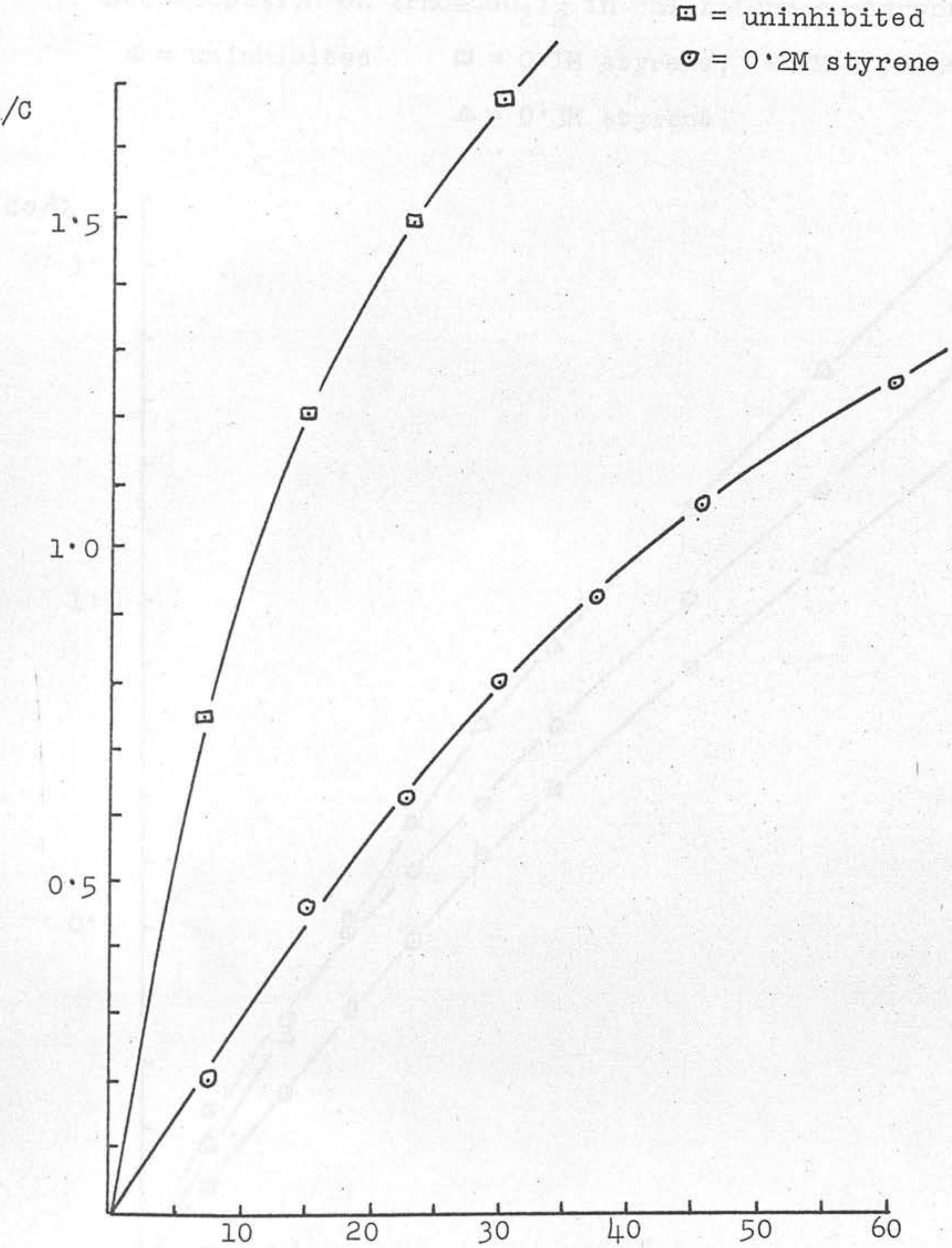
I	Mins.	0	7·5	15	22·5	30	37·5	45	60	75	90
0·1	$Cx10^2$	5·24	4·66	4·06	3·59	3·21	2·84	2·56	2·14	1·82	1·53
	lnCo/C	0·000	0·118	0·254	0·378	0·489	0·612	0·715	0·896	1·059	1·230
0·2	$Cx10^2$	4·55	4·07	3·58	3·18	2·82	2·44	2·18	1·78	1·50	1·25
	lnCo/C	0·000	0·110	0·239	0·359	0·476	0·622	0·737	0·936	1·111	1·292
0·3	$Cx10^2$	4·60	3·86	3·28	2·77	2·38	2·05	1·82	1·46	1·20	0·95
	lnCo/C	0·000	0·175	0·338	0·506	0·659	0·810	0·925	1·130	1·345	1·570

The plots of lnCo/C versus t are shown in graph VII and the resulting half-lives in the table below.

Styrene concentration (M)	0	0·1	0·2	0·3
$t_{\frac{1}{2}}$ (mins.)	36·5	43·3	43·5	31·7

Graph VI

Decomposition of $(PhC\equiv CCO_2)_2$ in dioxane.

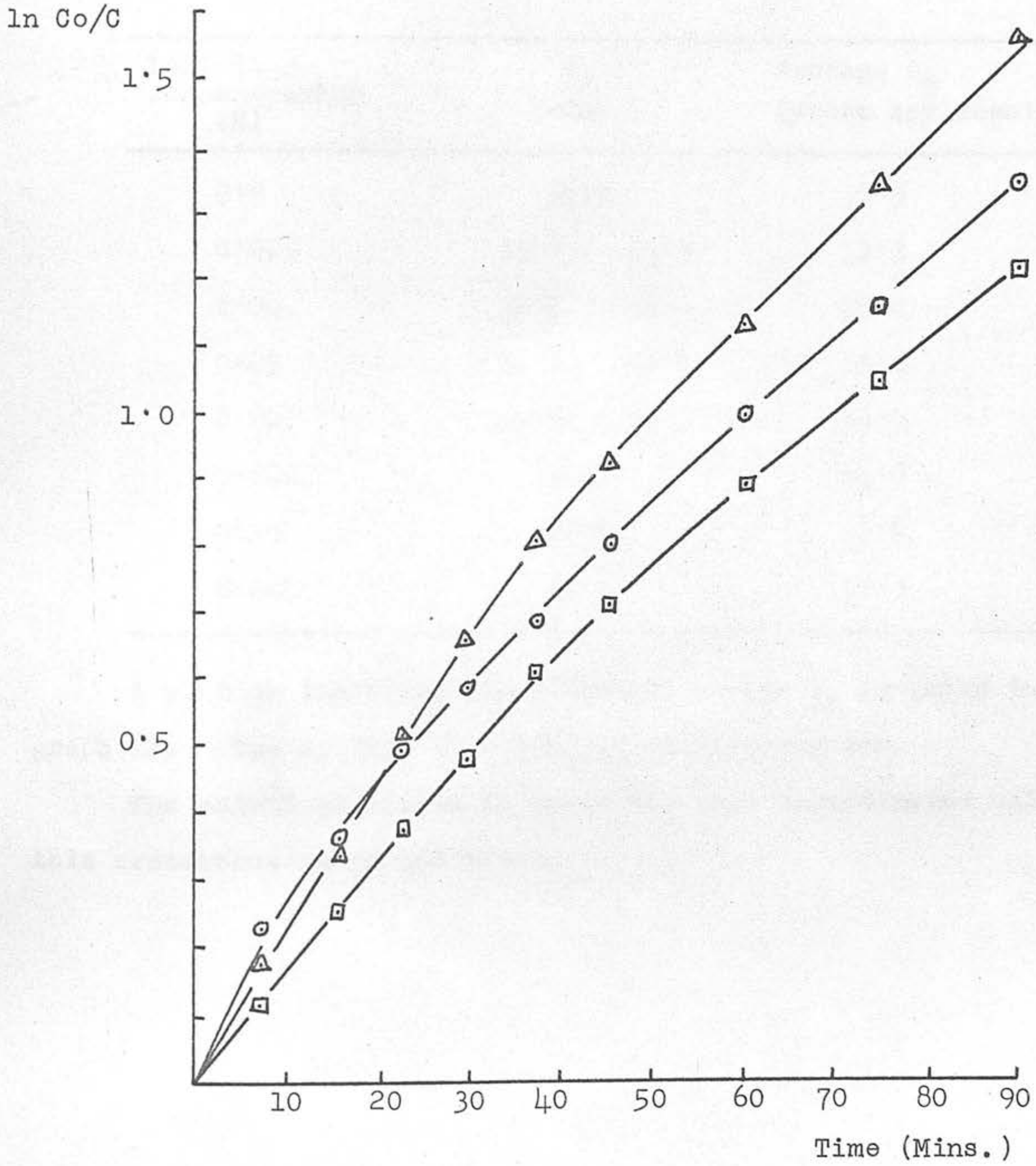


Graph VII

Decomposition of $(PhC\equiv CCO_2)_2$ in chloroform + styrene

⊙ = uninhibited ⊡ = 0·1M styrene; 0·2M styrene.

△ = 0·3M styrene



2.9.2. The decomposition in the presence of 3,4-dichlorostyrene inhibitor

The results with styrene indicated an optimum inhibitor concentration. A series of experiments was carried out in chloroform and the results are summarised in table XV.

The half-lives obtained from the plots of lnCo/C versus t (see graph VIII) are given in the table below.

Inhibitor concentration (M)	$t_{\frac{1}{2}}$ (mins.)		Average $t_{\frac{1}{2}}$ (where applicable)
0·0	36·5		36·5
0·025	53·0	53·5	53·3
0·04	56·2	54·2	55·2
0·05	57·7	56·0	56·8
0·06	56·5	55·5	56·0
0·075	54·8		54·8
0·10	52·8		52·8
0·20	47·3		47·3

A plot of inhibitor concentration versus $t_{\frac{1}{2}}$ is shown in graph IX. The optimum is 0·05M 3,4-dichlorostyrene.

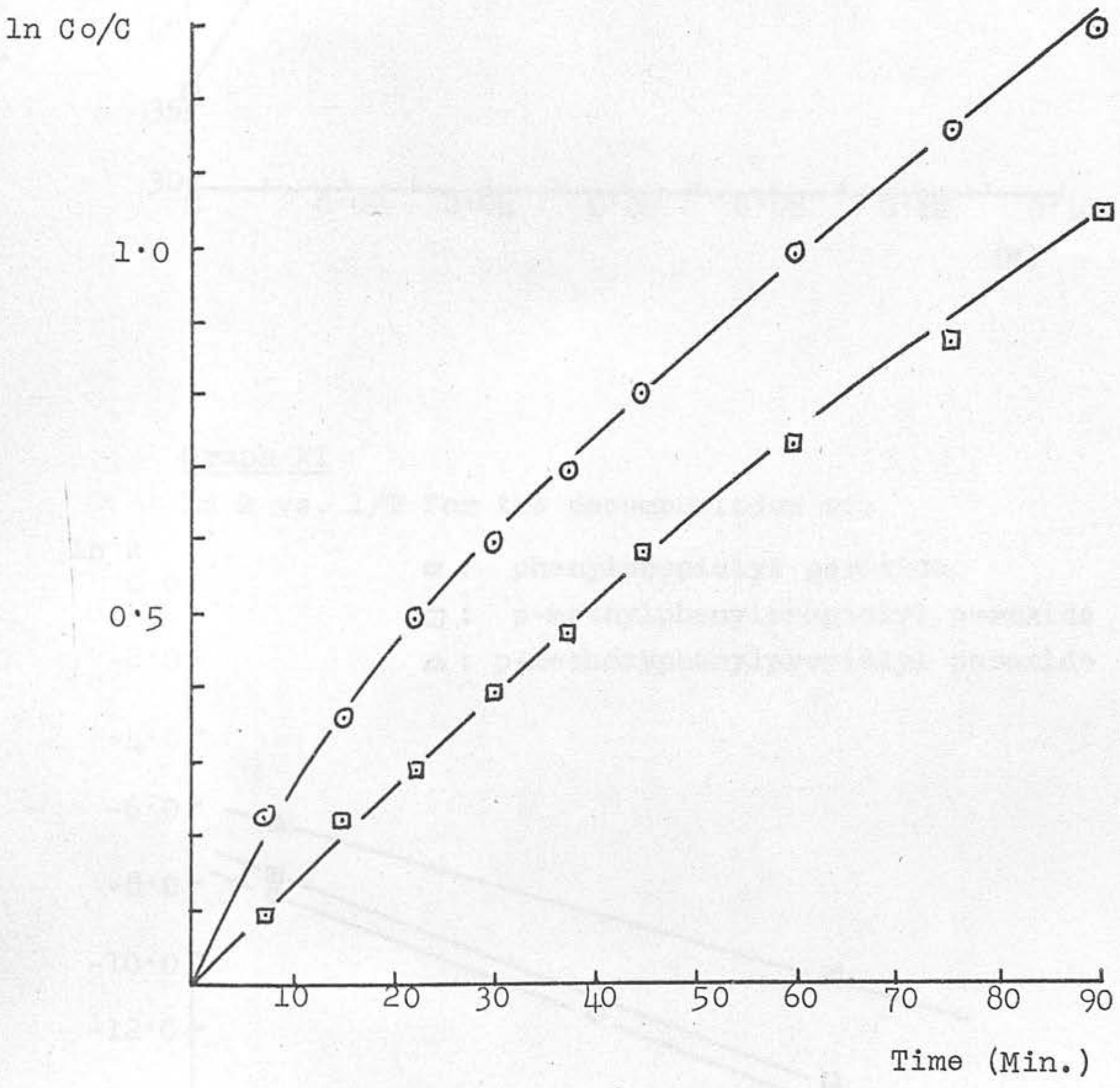
The solutions listed in table XVI were investigated using this concentration of inhibitor.

Graph VIII

Decomposition of $(PhC\equiv CCO_2)_2$ in chloroform

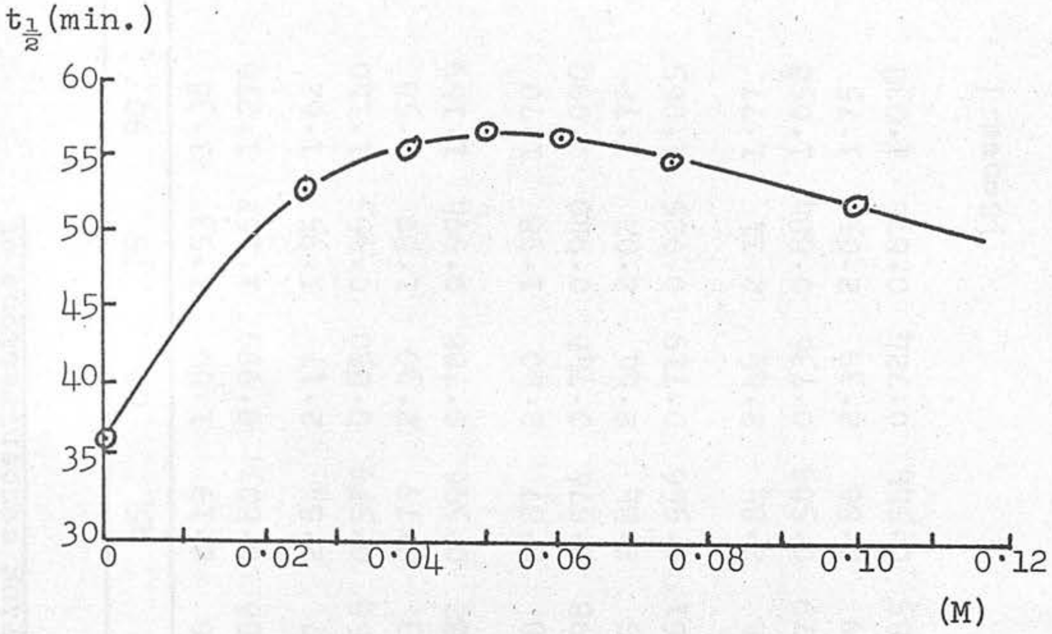
⊙ = uninhibited

⊡ = 0·05M 3,4-dichlorostyrene.



Graph IX

$t_{\frac{1}{2}}$ vs. concentration of 3,4-dichlorostyrene (M).



Graph XI

Ln k vs. 1/T for the decomposition of:

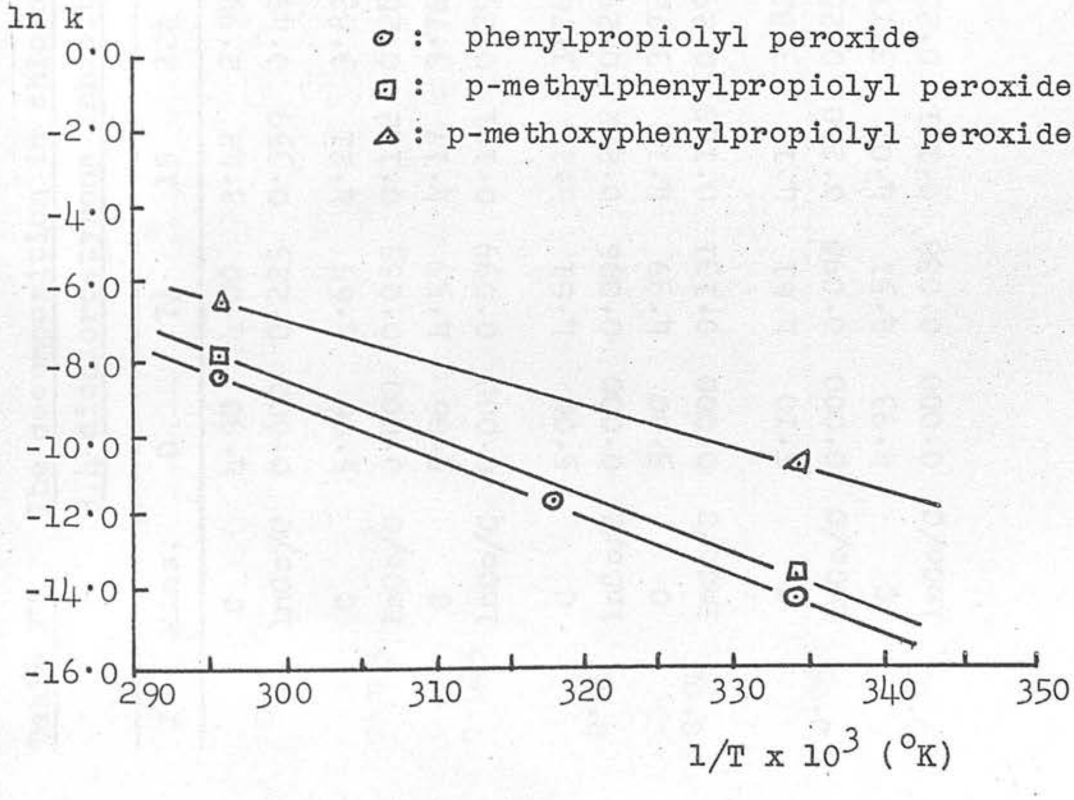


Table XV. The decomposition in chloroform with varying concentrations of 3,4-dichlorostyrene inhibitor

I	Mins.	0	7½	15	22½	30	37½	45	60	75	90
0	C	4·90	4·00	3·42	2·99	2·72	2·46	2·19	1·80	1·53	1·38
	lnCo/C	0·000	0·225	0·359	0·494	0·590	0·688	0·803	0·999	1·162	1·270
0·025	C	5·06	4·65	4·21	3·83	3·44	3·17	2·84	2·17	1·95	1·62
	lnCo/C	0·000	0·085	0·182	0·280	0·386	0·468	0·579	0·850	0·965	1·140
0·025	C	5·06	4·59	4·17	3·76	3·41	3·13	2·79	2·30	1·87	1·58
	lnCo/C	0·000	0·099	0·191	0·298	0·398	0·482	0·596	0·788	0·994	1·169
0·04	C	5·06	4·61	4·14	3·76	3·41	3·08	2·87	2·40	1·98	1·70
	lnCo/C	0·000	0·096	0·202	0·298	0·396	0·498	0·576	0·746	0·940	1·090
0·04	C	5·00	4·39	4·14	3·72	3·41	3·15	2·84	2·44	2·02	1·72
	lnCo/C	0·000	0·131	0·189	0·295	0·382	0·461	0·566	0·719	0·905	1·065
0·05	C	5·10	4·61	4·17	3·82	3·43	3·16	2·84	2·44	2·11	1·77
	lnCo/C	0·000	0·098	0·220	0·288	0·396	0·479	0·585	0·736	0·884	1·058
0·05	C	4·93	4·51	4·07	3·71	3·36	3·09	2·86	2·39	2·05	1·75
	lnCo/C	0·000	0·088	0·191	0·284	0·382	0·465	0·544	0·724	0·876	1·038

[Contd.]

Table XV [Contd.]

I	Mins.	0	7½	15	22½	30	37½	45	60	75	90
0·06	C	5·00	4·55	4·13	3·76	3·33	3·06	2·88	2·39	2·08	1·75
	lnCo/C	0·000	0·096	0·191	0·288	0·405	0·490	0·553	0·736	0·875	1·050
0·06	C	5·00	4·55	4·14	3·69	3·36	3·06	2·82	2·36	2·05	1·75
	lnCo/C	0·000	0·096	0·189	0·304	0·396	0·490	0·572	0·750	0·890	1·050
0·075	C	5·04	4·51	4·04	3·66	3·36	3·11	2·79	2·39	2·02	1·76
	lnCo/C	0·000	0·113	0·222	0·318	0·410	0·480	0·589	0·745	0·914	1·050
0·10	C	4·93	4·41	3·94	3·56	3·29	2·94	2·68	2·28	2·05	1·80
	lnCo/C	0·000	0·111	0·221	0·322	0·404	0·516	0·607	0·770	0·876	1·005
0·20	C	4·96	4·49	3·98	3·52	3·14	2·81	2·56	2·11	1·79	1·53
	lnCo/C	0·000	0·101	0·228	0·343	0·456	0·567	0·661	0·854	1·020	1·180

Table XVI. The decomposition in various solvents in the presence of 3,4-dichlorostyrene inhibitor

	Mins.	0	7·5	15	22·5	30	40	45	60	75	90
Cu	$C \times 10^2$	5·00	4·16	3·27	2·63	2·22	1·83	1·64	1·30	1·11	0·93
	$\ln C_o/C$	0·000	0·182	0·424	0·644	0·810	1·005	1·114	1·347	1·504	1·685
To	$C \times 10^2$	5·00	4·51	4·07	3·55	3·19	2·79	2·57	2·10	1·74	1·53
	$\ln C_o/C$	0·000	0·102	0·205	0·340	0·451	0·582	0·666	0·868	1·056	1·185
CCl_4	$C \times 10^2$	4·94	4·49	4·06	3·66	3·36	2·94	2·81	2·34	2·02	1·80
	$\ln C_o/C$	0·000	0·096	0·193	0·299	0·383	0·516	0·564	0·746	0·894	1·010
Be.	$C \times 10^2$	4·94	4·41	3·80	3·36	2·87	2·69	2·38	1·77	1·45	1·23
	$\ln C_o/C$	0·000	0·113	0·262	0·385	0·544	0·606	0·729	1·022	1·225	1·369

Cu: Cumene; To: Toluene; CCl_4: Carbon tetrachloride;
Be: Benzene.

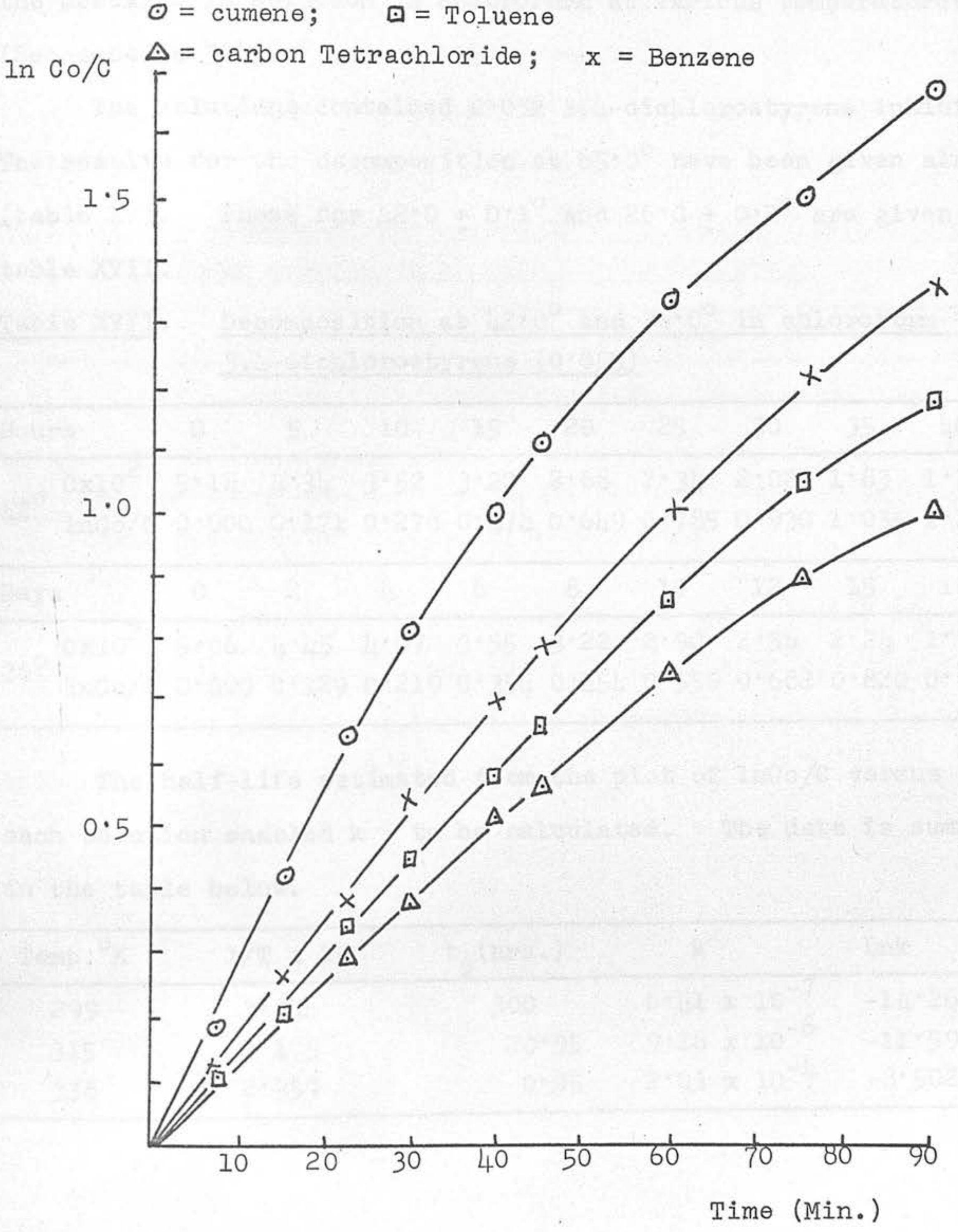
The plots of $\ln C_o/C$ versus t are shown in graph X, and the corresponding half-lives and k values are summarised in the table below.

Solvent	Cumene	Toluene	Carbon Tet.	Benzene
$t_{\frac{1}{2}}$(mins.)	25·2	47·3	56·0	41·2
$k \times 10^4$	4·580	2·440	2·059	2·800

Graph X

Decomposition of 0·05M $(PhC{\equiv}CCO_2)_2$ +

0·05M 3,4-dichlorostyrene.



2.9.3. Estimation of the energy of activation (Ea) for the decomposition of phenylpropiolyl peroxide

The energy of activation was estimated by the application of the Arrhenius' equation to the data from the decomposition of the peroxide in solution in chloroform at various temperatures. (See section 3.4).

The solutions contained 0·05M 3,4-dichlorostyrene inhibitor. The results for the decomposition at 65·0° have been given already, (table XV). Those for 42·0 ± 0·1° and 26·0 ± 0·1° are given in table XVII.

Table XVII. Decomposition at 42·0° and 26·0° in chloroform + 3,4-dichlorostyrene (0·05M)

Hours		0	5	10	15	20	25	30	35	40	45
42°	$C\times10^2$	5·14	4·34	3·52	3·20	2·68	2·34	2·02	1·83	1·70	1·55
	$\ln C_o/C$	0·000	0·171	0·278	0·474	0·649	0·785	0·930	1·035	1·108	1·118
Days		0	2	4	6	8	10	12	15	18	21
26°	$C\times10^2$	5·06	4·45	4·07	3·55	3·22	2·90	2·56	2·24	1·98	1·74
	$\ln C_o/C$	0·000	0·129	0·219	0·354	0·454	0·559	0·682	0·820	0·940	1·068

The half-life estimated from the plot of lnCo/C versus t for each solution enabled k to be calculated. The data is summarised in the table below.

Temp. °K	$1/T \times 10^3$	$t_{\frac{1}{2}}$(hrs.)	k	Lnk
299	3·344	300	$6{\cdot}41 \times 10^{-7}$	-14·260
315	3·175	20·95	$9{\cdot}18 \times 10^{-6}$	-11·598
338	2·959	0·95	$2{\cdot}03 \times 10^{-4}$	-8·502

The plot of lnk versus t is shown in graph XI. The slope is $1{\cdot}46 \times 10^4$, giving $E_a = 29{\cdot}1$ Kcal.mole.$^{-1}$

2.10. Kinetic studies on p-substituted phenylpropiolyl peroxides

The p-substituted peroxides were studied in chloroform solution. The concentration of the solutions was 0·05M.

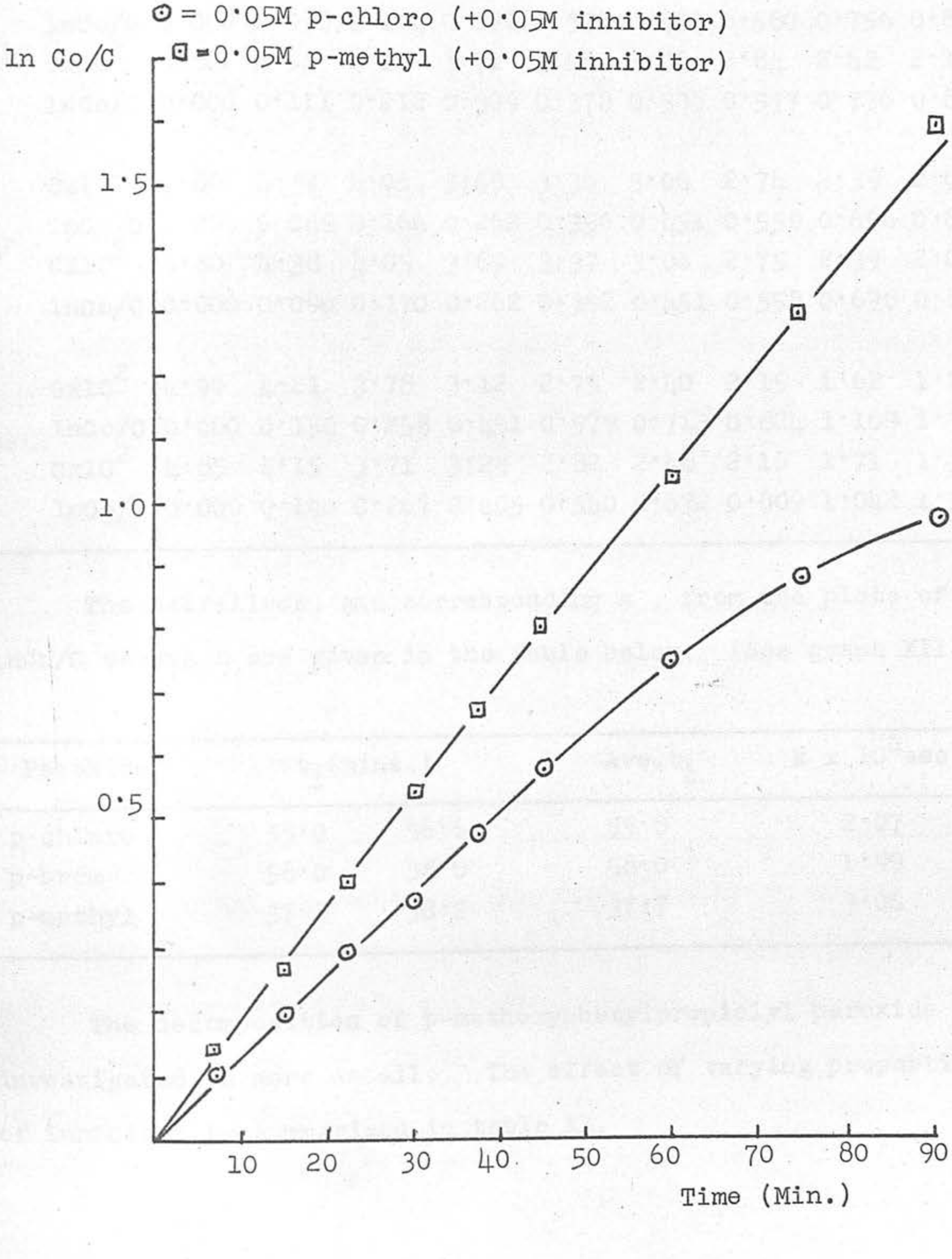
The results for the decomposition of p-chlorophenylpropiolyl peroxide are given in table XVIII.

Table XVIII. Decomposition of p-chlorophenylpropiolyl peroxide in chloroform at 65·0°. No inhibitor

Mins.	0	7·5	15	22·5	30	37·5	45	60	75	90
$C \times 10^2$	4·60	3·76	3·29	2·87	2·54	2·32	2·10	1·69	1·40	1·24
lnCo/C	0·000	0·202	0·338	0·472	0·594	0·684	0·783	0·999	1·190	1·310

From the plot of lnCo/C, $t_{\frac{1}{2}} = 37{\cdot}0$ mins.

The decomposition of the peroxides in the presence of 0·05M 3,4-dichlorostyrene was investigated. The results for p-chloro-, p-bromo- and p-methylphenylpropiolyl peroxides are summarised in table XIX.



Graph XII

Decomposition of p-substituted peroxides

Table XIX. Decomposition of p-substituted peroxides in chloroform + 0·05M 3,4-dichlorostyrene inhibitor

	Mins.	0	7·5	15	22·5	30	37·5	45	60	75	90
Cl	Cx10^2	5·08	4·60	4·18	3·76	3·48	3·15	2·84	2·38	2·10	1·89
	lnCo/C	0·000	0·098	0·194	0·297	0·377	0·477	0·580	0·756	0·882	0·985
	Cx10^2	5·06	4·54	4·10	3·71	3·46	3·06	2·84	2·42	2·10	1·80
	lnCo/C	0·000	0·111	0·212	0·309	0·378	0·504	0·577	0·736	0·879	1·031
Br	Cx10^2	4·80	4·39	4·06	3·69	3·36	3·06	2·74	2·39	2·02	1·76
	lnCo/C	0·000	0·089	0·166	0·262	0·356	0·451	0·559	0·696	0·861	1·005
	Cx10^2	4·80	4·38	4·05	3·69	3·37	3·06	2·75	2·39	2·01	1·76
	lnCo/C	0·000	0·090	0·170	0·262	0·352	0·451	0·558	0·696	0·870	1·005
Me	Cx10^2	4·90	4·21	3·78	3·12	2·75	2·40	2·15	1·62	1·29	0·98
	lnCo/C	0·000	0·150	0·258	0·451	0·579	0·713	0·824	1·109	1·334	1·618
	Cx10^2	4·85	4·15	3·71	3·23	2·82	2·48	2·16	1·71	1·32	0·97
	lnCo/C	0·000	0·140	0·267	0·405	0·540	0·672	0·809	1·042	1·303	1·610

The half-lives, and corresponding k , from the plots of lnCo/C versus t are given in the table below. (See graph XII).

Peroxide	$t_{\frac{1}{2}}$(mins.)		Ave.$t_{\frac{1}{2}}$	k x 10^4sec^{-1}
p-chloro	55·0	56·6	55·8	2·07
p-bromo	58·0	58·0	58·0	1·99
p-methyl	37·2	38·2	37·7	3·06

The decomposition of p-methoxyphenylpropiolyl peroxide was investigated in more detail. The effect of varying proportions of inhibitor is summarised in table XX.

Table XX. The decomposition of p-methoxyphenylpropiolyl peroxide

I	Mins.	0	2	4	6	8	10	12	14	16	20
0	Cx10^2	4·71	3·92	3·37	2·83	2·40	1·98	1·57	1·31	1·14	0·75
	lnCo/C	0·000	0·184	0·335	0·510	0·674	0·866	1·100	1·281	1·420	1·795
0·04	Cx10^2	4·65	4·00	3·46	2·80	2·38	2·01	1·70	1·43	1·16	0·86
	lnCo/C	0·000	0·150	0·296	0·508	0·670	0·839	1·040	1·220	1·286	1·690
0·05	Cx10^2	4·80	3·97	3·63	2·82	2·36	1·97	1·70	1·43	1·19	0·79
	lnCo/C	0·000	0·189	0·282	0·530	0·710	0·889	1·040	1·220	1·395	1·803
0·06	Cx10^2	4·76	4·11	3·37	2·97	2·37	2·15	1·71	1·47	1·21	0·93
	lnCo/C	0·000	0·147	0·346	0·474	0·698	0·796	1·020	1·180	1·370	1·635
0·10	Cx10^2	4·50	3·79	3·26	2·70	2·24	1·90	1·61	1·36	1·13	0·75
	lnCo/C	0·000	0·170	0·322	0·512	0·696	0·861	1·030	1·200	1·382	1·790
0·50	Cx10^2	4·57	3·73	3·26	2·57	2·20	1·80	1·45	1·220	1·02	0·69
	lnCo/C	0·000	0·190	0·339	0·574	0·733	0·933	1·149	1·330	1·504	1·900

The half-lives are listed in the table below.

Inhibitor concentration (M)	0	0·04	0·05	0·06	0·10	0·50
$t_{\frac{1}{2}}$ (mins.)	7·80	8·08	7·90	8·10	8·05	7·30

The results indicate that the added inhibitor has no effect on the rate of decomposition of p-methoxyphenylpropiolyl peroxide and this, coupled with the greatly increased rate compared with the other p-substituted derivatives suggests a different mechanism of decomposition. (See section 3.5). The first order rate constant corresponding to $t_{\frac{1}{2}}$ = 8·0 mins. is 1·45 x 10^{-3}sec.$^{-1}$

An estimation of the energy of activation (E_a) was obtained for the p-methyl- and p-methoxy- derivatives.

This was obtained by decomposing each in chloroform containing 0·05M 3,4-dichlorostyrene at two different temperatures, namely, 65·0° and 26·0°. The results obtained at the higher temperature have already been tabulated, those for 26·0° are given in table XXI.

Table XXI. The decomposition of p-methyl- and p-methoxy-phenylpropiolyl peroxides at 26·0°.

	Days	0	2	4	6	8	10	12
p-methyl	$C \times 10^2$	5·59	4·59	3·82	2·86	2·51	2·04	1·74
	$\ln C_o/C$	0·000	0·198	0·378	0·670	0·800	1·009	1·170
	Hours	0	4	8	12	16	20	24
p-methoxy	$C \times 10^2$	4·97	3·62	2·66	1·93	1·43	1·07	0·81
	$\ln C_o/C$	0·000	0·318	0·636	0·944	1·250	1·538	1·900

The half-lives and corresponding k values are given in the tables below. (See graph XI page 55).

p-methylphenylpropiolyl peroxide

Temp. °K	$1/T \times 10^3$	$t_{\frac{1}{2}}$(hrs.)	k (sec.$^{-1}$)	lnk
299	3·344	168	$1{\cdot}15 \times 10^{-6}$	-13·676
338	2·959	0·63	$3{\cdot}06 \times 10^{-4}$	- 8·092

Hence, E_a = 28·9 Kcal.mole.$^{-1}$

p-methoxyphenylpropiolyl peroxide

Temp. $^{\circ}$K	$1/T \times 10^3$	$t_{\frac{1}{2}}$(mins.)	k (sec^{-1})	lnk
299	3·344	534	$2{\cdot}16 \times 10^{-5}$	-10·743
338	2·959	8·0	$1{\cdot}45 \times 10^{-3}$	- 6·536

Hence, E_a = 21·7 Kcal.mole.$^{-1}$

SECTION 3

Discussion

3.1. The synthesis of phenylpropiolyl peroxide and p-substituted analogues

The synthesis of phenylpropiolyl peroxide from phenylpropiolyl chloride and sodium or hydrogen peroxide gave very low yields (ca. 6%) of impure material.

The method of Greene and Kazan[35] utilising the reaction between N,N'-dicyclohexylcarbodiimide and the free acid in the presence of 98% hydrogen peroxide gave good (ca. 60%) yields of high purity (98-99%) peroxide.

$$\mathrm{2PhC{\equiv}CCO_2H + H_2O_2 + 2R\text{-}N{=}C{=}N\text{-}R}$$

$$\longrightarrow \mathrm{(PhC{\equiv}CCO_2)_2 + 2R\text{-}NHCONHR}$$

(R = cyclohexyl).

It is noteworthy that in the absence of hydrogen peroxide, phenylpropiolic acid reacts with dicyclohexylcarbodiimide to form the acid anhydride.[45]

This method was adopted for all the peroxide preparations including the p-substituted derivatives. The synthesis of the latter necessitated the preparation of the substituted phenylpropiolic acids, none of which could be obtained commercially.

These were synthesised by the following route:

$$\mathrm{X\text{-}PhCHO + CH_2(CO_2H)_2 \xrightarrow[Pip.]{Pyr.} X\text{-}PhCH{=}CHCO_2H}$$

$$\mathrm{X\text{-}PhCH{=}CHCO_2H \xrightarrow[H^+]{EtOH} X\text{-}PhCH{=}CHCO_2Et.}$$

$$\mathrm{X\text{-}PhCH{=}CHCO_2Et\ + Br_2 \longrightarrow X\text{-}PhCHBrCHBrCO_2Et}$$

$$\text{X-PhCHBrCHBrCO}_2\text{Et} \xrightarrow[\text{EtOH}]{\text{KOH}} \text{X-PhC}\equiv\text{CCO}_2\text{H}$$

X = Cl, Br, Me. (In para position).

Since the use of the free acid and the ethyl ester lead to unexpected products (see section 2.5.2.), the p-methoxy analogue was prepared from the methyl ester.

3.2. The products of the decomposition of phenylpropiolyl peroxide in various solvents

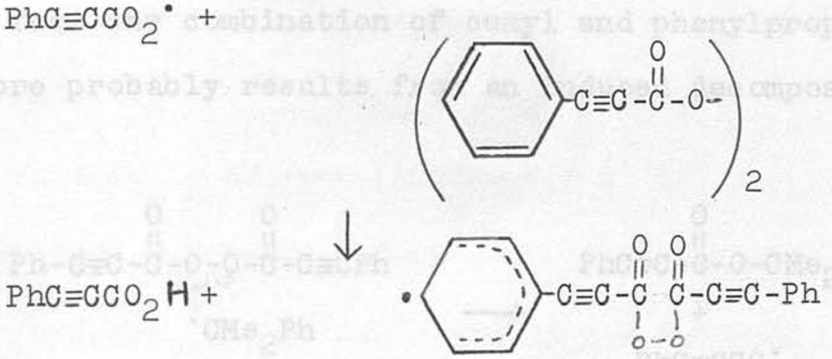
Phenylpropiolyl peroxide was decomposed in cumene, chloroform, toluene, benzene and carbon tetrachloride in order to investigate the reaction products.

The carbon dioxide and phenylpropiolic acid produced, in moles per mole of starting material are summarised in the table below.

Solvent	Carbon dioxide	Phenyl propiolic acid
Cumene	0·00	1·55
Chloroform	0·45	0·61
Toluene	0·24	0·86
Benzene	0·27	0·41
Carbon Tet.	0·42	0·00

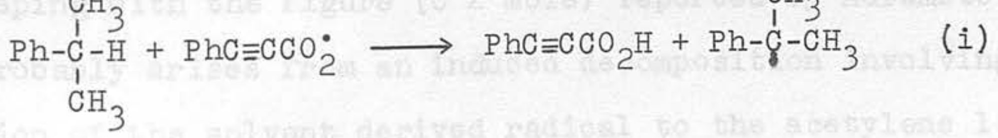
The low carbon dioxide yields, 0·0-0·45 mole per mole starting material, are in accord with the absence of products arising from the reaction of a phenyl ethynyl radical (PhC≡C·) either with the solvent to produce phenylacetylene or by dimerisation to produce 1,4-diphenybuta-1,3-diyne. The latter compound was absent from all the reaction mixtures and phenylacetylene was only present in the case of toluene and then only in very small yield (<0·04 mole).

The absence of phenylpropiolic acid from the reaction in carbon tetrachloride confirms that acid production arises only by reaction with a solvent molecule and not by aryl hydrogen abstraction. If the latter were the case, the carbon tetrachloride reaction would have yielded the acid by an induced decomposition:

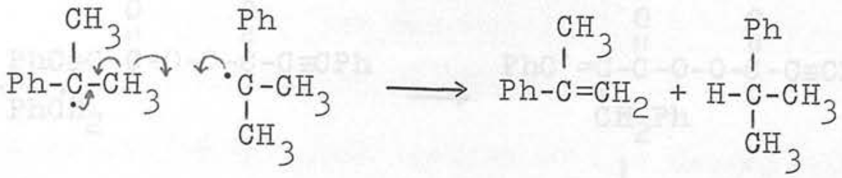


Bibenzyl (<0·04 mole) from toluene and hexachloroethane (<0·07 mole) from chloroform and carbon tetrachloride were the only products observed from the dimerisation of two solvent derived radicals. Again, the yield was very small, suggesting chain termination by this process is not a major pathway.

The absence of bicumyl from cumene is in part explained by the production of α-methylstyrene (0·01 mole) by the sequence:



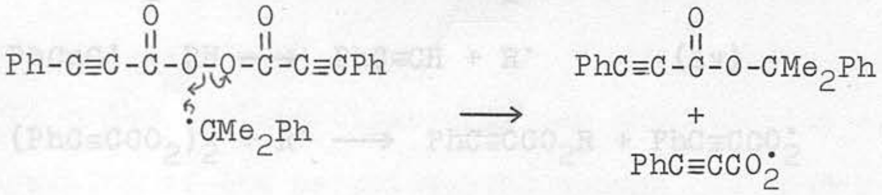
$$\mathrm{Ph}\text{-}\underset{\mathrm{CH_3}}{\overset{\mathrm{CH_3}}{\mathrm{C}}}\text{-}\mathrm{H} + \mathrm{PhC{\equiv}CCO_2^{\bullet}} \longrightarrow \mathrm{PhC{\equiv}CCO_2H} + \mathrm{Ph}\text{-}\overset{\mathrm{CH_3}}{\dot{\mathrm{C}}}\text{-}\mathrm{CH_3} \qquad \text{(i)}$$



$$\mathrm{Ph{-}\overset{\displaystyle CH_3}{\overset{|}{C}}{-}CH_3\ \ {}^{\bullet}\overset{\displaystyle Ph}{\overset{|}{\underset{\displaystyle CH_3}{\underset{|}{C}}}}{-}CH_3 \longrightarrow Ph{-}\overset{\displaystyle CH_3}{\overset{|}{C}}{=}CH_2 + H{-}\overset{\displaystyle Ph}{\overset{|}{\underset{\displaystyle CH_3}{\underset{|}{C}}}}{-}CH_3} \quad \text{(ii)}$$

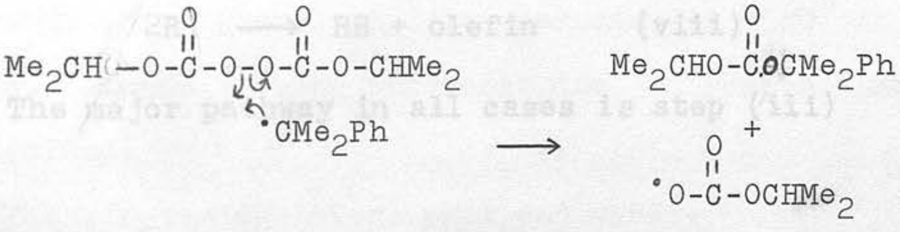
The disproportionation reaction (ii) is analogous to that found[46] in the decomposition of azocumene where both the coupling (94-95%) and the disproportionation (5-6%) products of the cumyl radical are observed.

The ester, cumyl phenylpropiolate, indicated by i.r. and n.m.r. analysis of the residue from the cumene reaction could arise from the combination of cumyl and phenylpropiolyl radicals, but more probably results from an induced decomposition of the type:



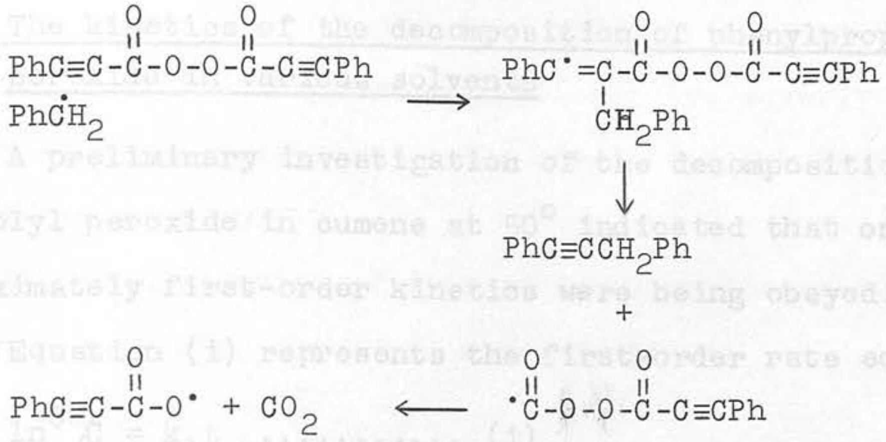
$$\mathrm{Ph{-}C{\equiv}C{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}C{\equiv}CPh + {}^{\bullet}CMe_2Ph \longrightarrow PhC{\equiv}C{-}\overset{O}{\overset{\|}{C}}{-}O{-}CMe_2Ph + PhC{\equiv}CCO_2^{\bullet}}$$

This type of induced decomposition has already been observed[47] with di-isopropylperoxydicarbonate in cumene.



$$\mathrm{Me_2CH{-}O{-}\overset{O}{\overset{\|}{C}}{-}O{-}O{-}\overset{O}{\overset{\|}{C}}{-}O{-}CHMe_2 + {}^{\bullet}CMe_2Ph \longrightarrow Me_2CHO{-}\overset{O}{\overset{\|}{C}}OCMe_2Ph + {}^{\bullet}O{-}\overset{O}{\overset{\|}{C}}{-}OCHMe_2}$$

The 1,3-diphenylpropyne (0·27 mole) produced in toluene is in keeping with the figure (0·2 mole) reported by Muramoto[37] *et al.*, and probably arises from an induced decomposition involving addition of the solvent derived radical to the acetylene linkage:



The reaction scheme below was deduced from the reaction products observed in the various decompositions studied.

$(PhC{\equiv}CCO_2)_2 \longrightarrow 2PhC{\equiv}CCO_2^{\cdot}$ (i)

$PhC{\equiv}CCO_2^{\cdot} \longrightarrow PhC{\equiv}C^{\cdot} + CO_2$ (ii)

$PhC{\equiv}CCO_2^{\cdot} + RH \longrightarrow PhC{\equiv}CCO_2H + R^{\cdot}$ (iii)

$PhC{\equiv}C^{\cdot} + RH \longrightarrow PhC{\equiv}CH + R^{\cdot}$ (iv)

$(PhC{\equiv}CCO_2)_2 + R^{\cdot} \longrightarrow PhC{\equiv}CCO_2R + PhC{\equiv}CCO_2^{\cdot}$ (v)

$PhC{\equiv}C^{\cdot} + R^{\cdot} \longrightarrow PhC{\equiv}CR$ (vi)

$2R^{\cdot} \longrightarrow R_2$ (vii)

$2R^{\cdot} \longrightarrow RH + \text{olefin}$ (viii)

The major pathway in all cases is step (iii)

3.3. The kinetics of the decomposition of phenylpropiolyl peroxide in various solvents

A preliminary investigation of the decomposition of phenylpropiolyl peroxide in cumene at 50° indicated that only approximately first-order kinetics were being obeyed.

Equation (i) represents the first-order rate equation;

$$\ln {}^{Co}/_{C} = k_1 t \;\ldots\ldots\ldots\ldots \quad (i)$$

(where Co = concentration of species at time zero; c = concentration of species at time t and k_1 = first-order rate constant).

The application of this to the data from the above experiment gave a line which deviated slightly from linearity indicating higher order kinetics and therefore induced decomposition of the peroxide was suspected.

In order to investigate further the kinetics of the decomposition of the peroxide, the scheme outlined below was applied. This is analogous to that proposed[13] for the induced decomposition of benzoyl peroxide in various solvents. Its applicability to the decomposition of phenylpropiolyl peroxide at 65·0° in cumene, benzene, toluene, carbon tetrachloride, chloroform and cyclohexane was examined.

The kinetic equations employed were:-

$$\mathrm{P} \xrightarrow{k_1} 2\mathrm{R} \qquad (ii)$$

$$2\mathrm{R} \xrightarrow{k_2} \mathrm{RR} \qquad (iii)$$

$$\mathrm{R} + \mathrm{P} \xrightarrow{k_3} \mathrm{X} + \mathrm{R} \qquad (iv)$$

where, P = peroxide; R = any free radical bringing about induced decomposition (i.e. assumes all radicals are equally reactive, which need not necessarily be the case), and X = Product(s) of the chain decomposition.

The concentration of free radicals at the steady state is expressed by making the usual approximation:

$$\frac{dR}{dt} = k_1P - k_2R^2 \simeq 0 \qquad \text{(v)}$$

$$\therefore\ R = \sqrt{k_1P/k_2}$$

Thus the rate of decomposition of peroxide is given by,

$$\frac{-dP}{dt} = k_1P + k_3PR = k_1P + k_3\sqrt{\frac{k_1}{k_2}}\ .\ P^{3/2}$$

$$= k_1P + k_iP^{3/2} \qquad \text{(vi)}$$

where $k_i = k_3 . \sqrt{k_1/k_2}$

Equation (vi) on integration yields,

$$\ln\frac{a + \sqrt{P}}{\sqrt{P}} - \ln\frac{a + \sqrt{P_o}}{\sqrt{P_o}} = \frac{k_1t}{2} \qquad \text{(vii)}$$

$$\text{where } \underline{a} = \frac{k_1}{k_i} \qquad \text{(viii)}$$

The value of the constant a in any solvent may be determined by using the data from two runs with different initial concentrations of peroxide and with samples taken at the same time intervals in the two runs. After the same time, the value of the right-hand member of equation (vii) is the same for both runs and the logarithmic terms may be equated. If P_1 and P_2 are the peroxide concentrations at equal times in the two runs, then:

$$\ln \frac{a + \sqrt{P_1}}{\sqrt{P_1}} = \ln \frac{a + \sqrt{P_2}}{\sqrt{P_2}} + \ln C \qquad (ix)$$

i.e.

$$\frac{1}{\sqrt{P_1}} = \frac{C}{\sqrt{P_2}} + \frac{C-1}{a} \qquad (x)$$

If the system follows the scheme then a plot of $1/\sqrt{P_1}$ versus $1/\sqrt{P_2}$ should be a straight line from whose slope and intercept <u>a</u> may be calculated.

From equation (vii) a plot of $\ln [(a + \sqrt{P})/\sqrt{P}]$ versus t should also be linear and from whose slope the first-order rate constant k_1 may be calculated.

An alternative solution of equation (x) is offered by the fact that a series of lines defined by this equation should be coincident. Moreover, as $1/\sqrt{P_1}$ could be plotted against $1/\sqrt{P_2}$ the point of coincidence should lie on the line y = x.

The lines under consideration may be represented by the equations

$$-y + c_1 x + \frac{c_1 - 1}{a} = 0$$

$$-y + c_2 x + \frac{c_2 - 1}{a} = 0$$

$$-y + c_3 x + \frac{c_3 - 1}{a} = 0$$

These lines are coincident if and only if the determinant, $\triangle$ below, is zero.

$$\Delta = \begin{vmatrix} -1 & C_1 & (C_1-1)/a \\ -1 & C_2 & (C_2-1)/a \\ -1 & C_3 & (C_3-1)/a \end{vmatrix} = \frac{1}{a}\begin{vmatrix} -1 & C_1 & C_1-1 \\ -1 & C_2 & C_2-1 \\ -1 & C_3 & C_3-1 \end{vmatrix} = \frac{1}{a}\begin{vmatrix} -1 & C_1 & C_1 \\ -1 & C_2 & C_2 \\ -1 & C_3 & C_3 \end{vmatrix}$$

As two columns in the last group are the same, $\Delta = 0$ and hence the three lines will be coincident. Similarly, it may be shown that they coincide with the line $x = y$, the point of coincidence being $x = y = -\frac{1}{a}$.

In the present investigation, three solutions (labelled C_A, C_B and C_C) of differing initial peroxide concentration were used for each solvent, enabling three lines to be constructed for $1/\sqrt{P_1}$ versus $1/\sqrt{P_2}$.

With the exception of cumene these lines were coincident in the third quadrant. As this point was so close to zero as to be almost indistinguishable from it, in the case of chloroform, and the results for carbon tetrachloride gave almost parallel lines, a more accurate estimate of the point of coincidence was obtained by calculating the best straight line by the method of least squares. This was performed on a KDF 9 computer using a programme supplied by Dr. Lowe of this department. From the slope (m) and intercept (c) so obtained a value for <u>a</u> was calculated. The figures are summarised in table X section 2.8.3.

No figure is given for cumene as the slopes of the three curves of $1/\sqrt{P_1}$ versus $1/\sqrt{P_2}$ were >1, resulting in a negative value for <u>a</u> and an unreal value for $\ln[(a + \sqrt{P})/\sqrt{P}]$ when $a > \sqrt{P}$.

In this case, the best straight line was not calculated and the investigation was carried no further.

The figures of 0·455 and 0·810 calculated for a for benzene and toluene respectively were disregarded due to the magnitude of the error term. From the other two figures in each case, plots of $\ln [(a + \sqrt{P})/\sqrt{P}]$ versus t were constructed using $\sqrt{P}$ from each of the solutions C_A, C_B and C_C. From the slopes of the resulting three graphs for each solvent a value of k_1 was found. Two values only were obtained for toluene as one plot was curved.

In the case of carbon tetrachloride, the values of a were very small and similar. An average value of a (0·045) was taken and this gave three plots, calculated as described for benzene and toluene, only one of which was linear. The value of k_1 calculated from this was $5{\cdot}6 \times 10^{-5}$ sec.^{-1}

The wide variation in the value of a obtained for chloroform is attributed to the fact that the lines obtained for $1/\sqrt{P_1}$ versus $1/\sqrt{P_2}$ were not strictly linear. The only meaningful a value, namely 1·701 gave three curves when substituted in equation (vii). No value for k_1 was found.

As mentioned in the experimental section, cyclohexane gave unsatisfactory results for the initial plot of lnCo/C versus t and was not investigated further.

The average values of a and k_1 found are summarised below:

	Benzene	Toluene	Carbon Tet.
a	0·234	0·320	0·045
$k_1 \times 10^4 \text{sec}^{-1}$	1·46	1·66	0·56

In a recent brief communication[37] on the decomposition of phenylpropiolyl peroxide in toluene at 70° a value for k_1 of $5 \cdot 9 \times 10^{-5}$ is given. The results obtained in the present study at 65° are considerably higher than this for k_1 with the exception of carbon tetrachloride.

Although no experimental details are given in the communication, a kinetic scheme and experimental technique similar to those used here are indicated. The kinetic equation quoted, rate = $k_1P + k_2P^{3/2}$, suggests that the induced decomposition was studied rather than an inhibited decomposition using galvinoxyl or a similar radical trapping technique. This is also suggested by the concentration range of peroxide solution used (i.e. 0·01 - 0·10M) which is similar to that of the present study. The excess stable free radical technique[20] requires concentrations of the order 10^{-5}M.

The discrepancy between the results suggests that the scheme is not altogether satisfactory as does the non-uniformity of the results of the present study.

The scheme assumes that the higher order kinetics arise from an induced decomposition brought about by radicals normally present as a result of decomposing phenylpropiolyl peroxide, a situation already verified by Nozaki and Bartlett[13] for benzoyl peroxide in various solvents. (It should be noted, however, that these authors gave no details for the decomposition in cumene, suggesting perhaps a similar situation to that of the present study.)

The radicals R, in the scheme, in this case come exclusively from peroxide decomposition and the further assumption made is that every other product of the reaction can be formulated as arising in a similar manner. Any chain transfer with the solvent is envisaged as producing radicals comparable in reactivity to those already present. If this were true then only the products and not the kinetics would be affected.

The fact that of all the solvents studied only benzene and possibly toluene give results compatible with the scheme suggests this assumption is incorrect. If induced decomposition is taking place under the influence of radicals formed by transfer with the solvent - a situation known to be present in cumene by the presence of α-methyl styrene in the products - there is no reason to believe that a trichloromethyl radical from chloroform and a benzyl radical from toluene should be equal in reactivity and indeed the results suggest the opposite.

3.4. The kinetics of the decomposition of phenylpropiolyl peroxide in the presence of an inhibitor, at 65·0°.

In order to eliminate the induced decomposition discussed above and render the kinetics as near first-order as possible, the effect of varying quantities of inhibitor on the reaction rate was studied, using a fixed concentration of peroxide throughout (viz., 0·05M).

The work of Nozaki and Bartlett[13] on the decomposition of benzoyl peroxide in dioxane in the presence of styrene as inhibitor prompted a similar investigation with phenylpropiolyl peroxide.

The half-life for the decomposition was found to be 6·9 mins., in the case of the uninhibited reaction and 26·0 mins., in the presence of a 2·6 molar excess of styrene.

The three-fold increase in the half-life in the presence of styrene confirmed the inhibitory nature of the latter. However, the short half-life (ca. 7 mins.) of the peroxide in dioxane rendered it an unsuitable solvent for the investigation.

In a similar investigation in chloroform an optimum inhibitor concentration was indicated by the results:-

Styrene concentration (M)	0	0·1	0·2	0·3
$t_{\frac{1}{2}}$(mins.)	36·5	43·3	43·5	31·7

Too great an inhibitor concentration resulted in an increase in the reaction rate.

3,4-Dichlorostyrene resulted in an even larger increase in the half-life indicating that it was a more efficient inhibitor. Moreover, a four-fold excess of the inhibitor did not increase the rate above that for the uninhibited case, as can be seen from the table below:-

Inhibitor concentration (M)	0	0·025	0·04	0·05	0·06	0·075	0·10	0·20
$t_{\frac{1}{2}}$(mins.)	36·5	53·3	55·2	56·8	56·0	54·8	52·8	47·3

From the plot of inhibitor concentration (M) versus $t_{\frac{1}{2}}$ (mins.) (Graph IX) an optimum inhibitor concentration of 0·05M was evident.

This corresponded to equimolar quantities of peroxide and inhibitor.

The data for the decomposition in the presence of this concentration of inhibitor gave a plot of lnCo/C versus t which was almost linear and which gave a first-order rate constant of $2{\cdot}03 \times 10^{-4}$ sec.$^{-1}$

The decompositions studied in the previous section were re-investigated in the presence of 0·05M 3,4-dichlorostyrene (i.e. the optimum inhibitor concentration for chloroform). The half-lives and first-order rate constants calculated from the plot of lnCo/C versus t for these decompositions are given in the table below. Also given are the values of k_1 (where applicable) calculated previously.

Solvent	Chloroform	Cumene	Toluene	Benzene	Carbon Tet.
$t_{\frac{1}{2}}$(mins.)	56·8	25·2	47·3	41·2	56·0
$k_1 \times 10^4$	2·03	4·58	2·44	2·80	2·06
*$k_1 \times 10^4$	-	-	1·66	1·46	0·56

* From section 3.3.

The discrepancy between k_1 as calculated by the two methods can be attributed to the short-comings of the scheme in section 3.3 already discussed and to the fact that the optimum inhibitor concentration in solvents other than chloroform may not be 0·05M.

The energy of activation for the decomposition of phenylpropiolyl peroxide was obtained by application of the Arrhenius' equation (xi) to the data from the decomposition in chloroform at various temperatures (See section 2.9.3.)

$$\frac{d\ln k}{dT} = {}^{E_a}/_{RT^2} \qquad \text{(xi)}$$

(k = 1st order rate constant; R = gas constant = 1·99 cal. deg. mole^{-1}; T = temperature in $^{\circ}$K).

On integration this gives:-

$$\ln k = {}^{-E_a}/_{RT} + \ln A \qquad \text{(xii)}$$

E_a was calculated from the slope of the graph (No.XI) of lnk versus t.

$$\text{Slope} = -1{\cdot}46 \times 10^{4}; \quad \ln A = -8{\cdot}35$$

$$\therefore \; {}^{E_a}/_{R} = 1{\cdot}46 \times 10^{-4}$$

$$\therefore \; E_a = 1{\cdot}99 \times 1{\cdot}46 \times 10^{-4} = 29{\cdot}1 \text{ Kcal.mole}^{-1}$$

This figure compares favourably with that of 30 Kcal.mole^{-1} for benzoyl peroxide[3] and similar figures for related peroxides.[1,2] An estimation of the accuracy of the terms T and k_1 in equation (xii) indicates that a 1° difference in temperature alters E_a by 4% whereas a ten-fold difference in k only alters the value by 2%. Obviously, the limiting figure for an accurate estimate is the value for T. For this reason, the reactions were carried out in a thermostatically controlled bath, the temperature being controlled to ± 0·1°.

3.5. The decomposition of p-substituted phenylpropiolyl peroxides in chloroform at 65·0°.

The decompositions of the p-substituted peroxides were investigated in chloroform with a view to constructing a Hammett $\sigma\rho$ plot analogous to that already discussed for benzoyl peroxide.[3] (Section 1.2.2.)

A preliminary decomposition of p-chlorophenylpropiolyl peroxide without added inhibitor gave $t_{\frac{1}{2}}$ = 37·0 mins. This is similar to the parent peroxide (viz., 36·5 mins.). Moreover, the decomposition of the p-chloro- and p-bromo- peroxides in chloroform with 0·05M 3,4-dichlorostyrene inhibitor gave half-lives of 55·8 and 58·0 mins. respectively which again were similar to the corresponding figure for the parent compound (56·8 mins.).

A small increase in the rate was observed with p-methylphenylpropiolyl peroxide, $t_{\frac{1}{2}}$ in this case being 37·7 mins. However, the p-methoxy analogue had $t_{\frac{1}{2}}$ = 8·0 mins., and this figure remained constant over an inhibitor concentration range of 0·0 to 0·5M.

The results are summarised in the table below:-

Peroxide	Parent	p-Cl	p-Br	p-Me	p-MeO
$t_{\frac{1}{2}}$(mins.)	56·8	55·8	58·0	37·7	8·0
$k_1 \times 10^4 \mathrm{sec}^{-1}$	2·03	2·07	1·99	3·06	14·5

The figures indicate that all, except the p-methoxy compound, appear to be undergoing a similar type of decomposition. The electron attracting chlorine and bromine substituents have not altered the rate appreciably whereas the electron repelling methyl group has slightly increased it. This latter is in keeping with the observation for benzoyl peroxide with electron repelling groups (q.v. section 1.2.2.).

The observed rate for the p-methoxy compound suggests the possibility of a different pathway for the decomposition and the possibility of a non-homolytic decomposition cannot be ruled out[29] (See section 1.2.3.). If the rate enhancement were simply due to the ability of the triple bond to increase the electron transfer from the p-methoxy group to the central O-O bond and hence weaken this by increased dipole-dipole interaction, a similar effect should be observed with the p-methyl compound. That this is not the case supports the view that an alternative mechanism is in operation. This is also indicated by the independence of the rate on inhibitor concentration, and by a consideration of activation energies. These are summarised below:

Peroxide	Parent	p-Me	p-MeO
E_a Kcal.mole^{-1}	29·1	28·9	21·7

The figures for the parent and p-methyl compound are analogous to those for benzoyl and related peroxides undergoing homolytic scission. That for the p-methoxy compound is considerably less.

3.6. Conclusion

Phenylpropiolyl peroxide undergoes an induced decomposition in a variety of solvents as indicated by the deviation from linearity of a plot of $\ln C_o/C$ versus t, the increase in rate with increase in peroxide concentration and by the observed products of the reactions.

Further study is necessary to elucidate fully the kinetics of the decomposition both of the parent peroxide and its p-substituted analogues as it does not seem to be as straightforward as the scheme proposed in section 3.3.

A quantitative product study similar to that already undertaken for benzoyl peroxide[48] would enable a more accurate and detailed kinetic scheme to be drawn up and hence the derivation of a more realistic kinetic equation.

Alternatively, decomposition in the presence of galvinoxyl as a radical scavenger would give the first-order rate constant directly by spectroscopic measurement[20] of the decrease in intensity of the galvinoxyl absorption. However, this would give no indication of the kinetic pathway.

PART II

Stereospecificity in free radical reactions.

SECTION I

Introduction

1.1. The concept of bridged radicals

A bridging mechanism to account for the observed stereochemistry has been proposed[49] for both addition and substitution reactions involving free radicals. However, in the majority of cases, alternative explanations are not ruled out by the experimental results.

1.2. Addition reactions to Olefins

The addition of hydrogen bromide to olefins under non-polar conditions is one of the classical free radical reactions.

Both Hey[50] and Kharash[51] independently proposed a free radical chain mechanism for the anti-Markownikoff addition of hydrogen bromide to allyl bromide:-

$$Br^{\cdot} + BrCH_2CH_2{=}CH_2 \longrightarrow BrCH_2\dot{C}HCH_2Br$$

$$BrCH_2{}^{\cdot}CHCH_2Br + HBr \longrightarrow BrCH_2CH_2CH_2Br + Br^{\cdot}$$

Initial dissociation of the hydrogen bromide may be effected by peroxide decomposition or by photolysis with U.V. light, the direction of addition being determined by the stability of the intermediate radical[52] or the strength of the new bond formed.[53] Termination steps are probably radical-radical combinations.

While the synthetic applications of the reaction have been explored extensively,[54] the mechanistic details were overlooked until Goering, Abell and Aycock[55] observed a stereoselectivity in the addition of hydrogen bromide to 1-bromocyclohexene and 1-methylcyclohexene yielding <u>cis</u>-1-2-dibromocyclohexane and <u>cis</u>-1-methyl-2-

bromocyclohexane respectively. This prompted the investigation of the stereochemistry of free radical addition reactions and reopened the question of the mechanism.

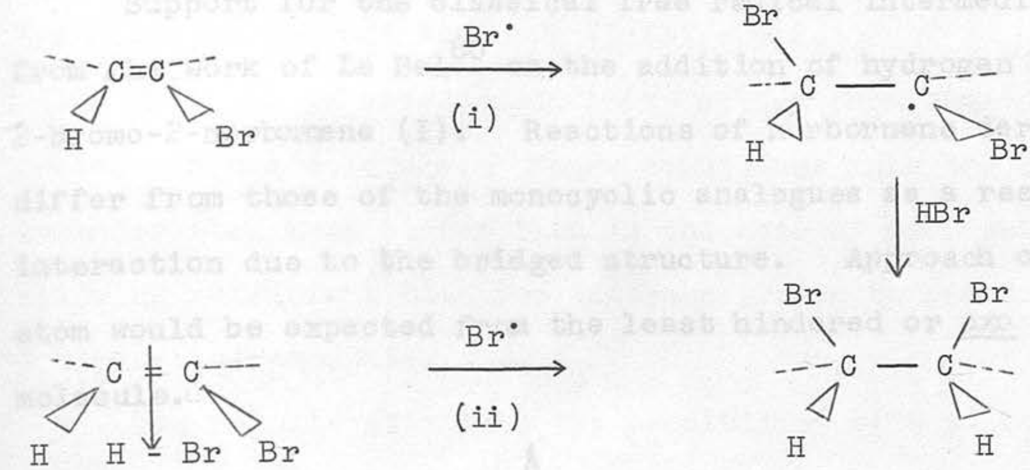
The original proposals of Hey and Kharash give no suggestion of stereospecificity and, in general, addition reactions of free radicals to olefins are expected to proceed by way of planar radical intermediates, with products determined largely by thermodynamic control.

A substantial number of hydrogen bromide additions now have been shown to proceed stereospecifically by a trans addition of the elements of hydrogen and bromine and to be independent of thermodynamic stability in the isomer produced. These include both cyclic and non-cyclic olefins.

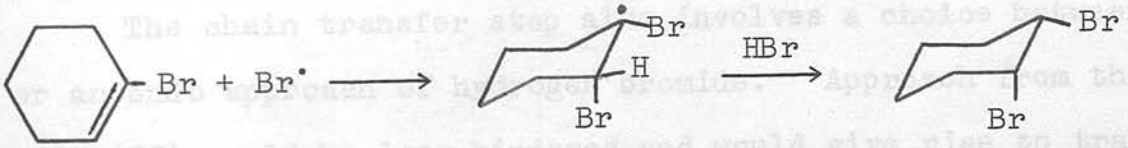
Several rationalisations have been offered to account for the preference for trans addition. Goering[55] et al. suggest a bridged or at least resonating bromine atom, holding both carbons of the double bond in fixed conformation until hydrogen abstraction completes the structure from the side opposite the bromine bridge. This bridging mechanism is analogous to that proposed and recently verified[56] for the ionic addition of bromine to double bonds.

A second possibility is that the hydrogen abstraction step follows the bromine atom addition to the pi bond so rapidly that changes in conformation of the initially formed bromoalkyl radical do not have a chance to take place.[57] (Path (i)).

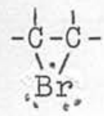
Path (ii) illustrates the formation of a complex[57,58] between the olefin and the hydrogen bromide. Formation of such an intermediate ensures that collision with a bromine atom gives a simultaneous attachment of the attacking bromine and breaking of the H-Br bond of the complexed hydrogen bromide. This step bonds the hydrogen and frees a new bromine atom to continue the chain.



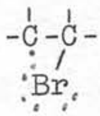
The Goering[7] model to account for:-



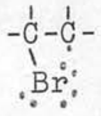
is proposed as a three membered cyclic intermediate with possible structures:-



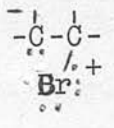
A



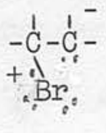
B



C



D

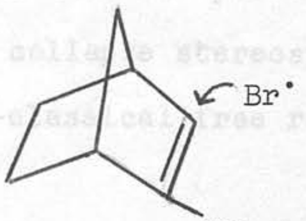


E

An immediate objection to structure A is the nine electrons in the outermost shell of the bromine. (cf. the bromonium ion Br^+ with eight). The other structures satisfy Pauling's[59] conditions for the formation of a stable three-electron bond.

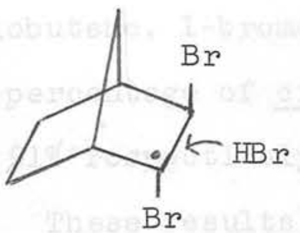
Evidence for or against the three proposed rationalisations is so far inconclusive.

Support for the classical free radical intermediate comes from the work of Le Bel[60] on the addition of hydrogen bromide to 2-bromo-2-norbornene (I). Reactions of norbornene derivatives differ from those of the monocyclic analogues as a result of steric interaction due to the bridged structure. Approach of a bromine atom would be expected from the least hindered or <u>exo</u> side of the molecule.

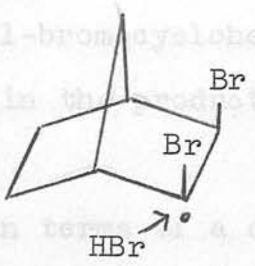


I

The chain transfer step also involves a choice between an exo or an endo approach of hydrogen bromide. Approach from the exo side (II) would be less hindered and would give rise to <u>trans</u>-2,3-dibromonorbornane. Approach from the more hindered endo side (III) would give rise to exo-<u>cis</u>-2,3-dibromonorbornane.



II

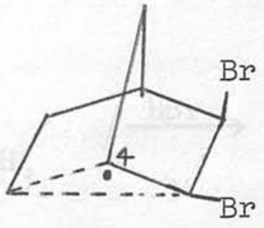


III

The observed product ratio is II:III = 5:2.

The lack of stereospecificity arises from steric repulsions present in the molecule. These repulsions make the chain transfer step much slower than in the case of monocyclic olefins - allowing sufficient time for interconversion to occur resulting in a mixture of products.

The results eliminate the possibility of a pi-complex which would be expected to collapse stereospecifically and also the possibility of a non-classical free radical (IV).



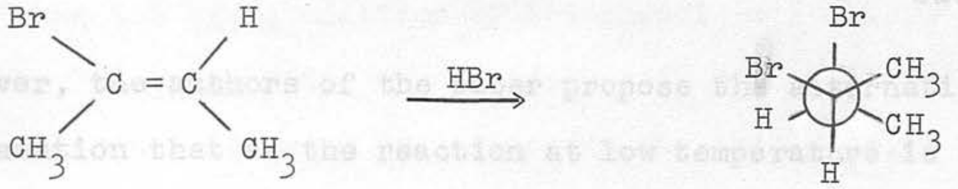
IV

Such an intermediate radical would give rise to 1,7-dibromonorbornane by chain transfer at C-4. No such compound was detected.

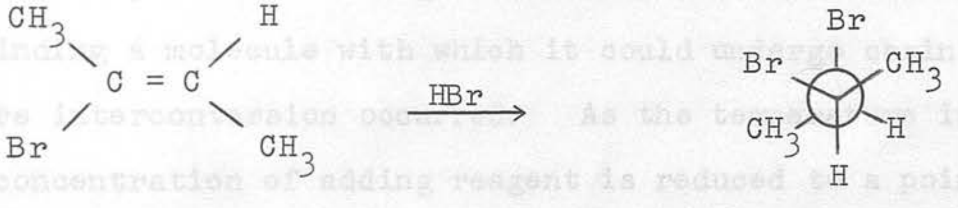
The bridged radical mechanism requires that all hydrogen bromide additions are stereospecific. That this is not the case has been shown[61] by the room temperature addition to 1-bromocyclobutene, 1-bromocyclopentene and 1-bromocycloheptene in which the percentage of *cis* isomer present in the products is 79%, 94% and 91% respectively.

These results are interpreted in terms of a classical free radical intermediate and the variation in selectivity attributed to a balance between mechanistic preference for a *trans* addition and steric inhibition to formation of the resulting *cis* isomers.

The addition[57] of hydrogen bromide to *cis*- and *trans*-2-bromo-2-butene at -80° gives 100% of the product resulting from *trans* addition.

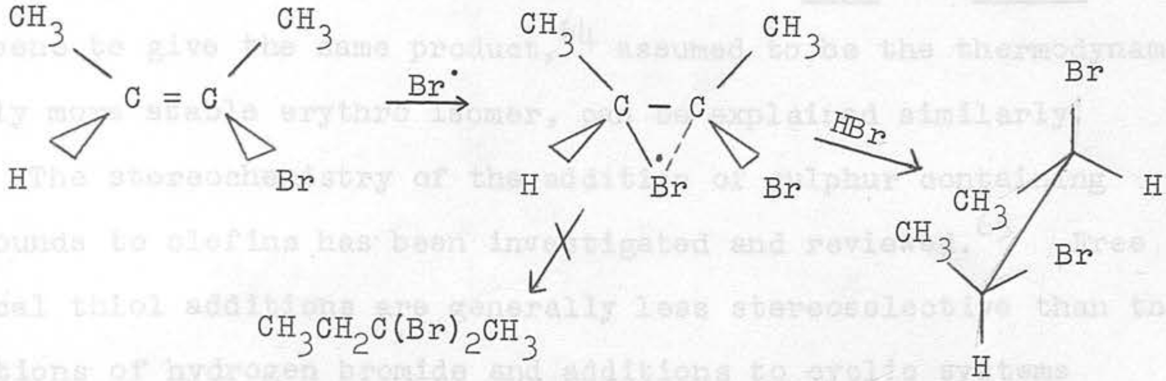


Erythro



Threo

As the temperature is raised the stereospecificity decreases so that at room temperature roughly the same mixture of products is obtained from either olefin. Skell[62] suggests that the results are best explained with an unsymmetrical bridged radical intermediate, resonance stabilisation of the α-halo radical resulting in greater radical character at the bromine bearing carbon.



2,2-dibromo butane

Erythro-2-3-dibromo butane

However, the authors of the paper propose the alternative explanation that as the reaction at low temperature is carried out in liquid hydrogen bromide, a considerable excess of the adding reagent is present allowing an intermediate free radical every chance of finding a molecule with which it could undergo chain transfer before interconversion occurred. As the temperature is raised, the concentration of adding reagent is reduced to a point where some of the intermediate radicals have time to interconvert before encountering a molecule of hydrogen bromide with which they could undergo transfer.

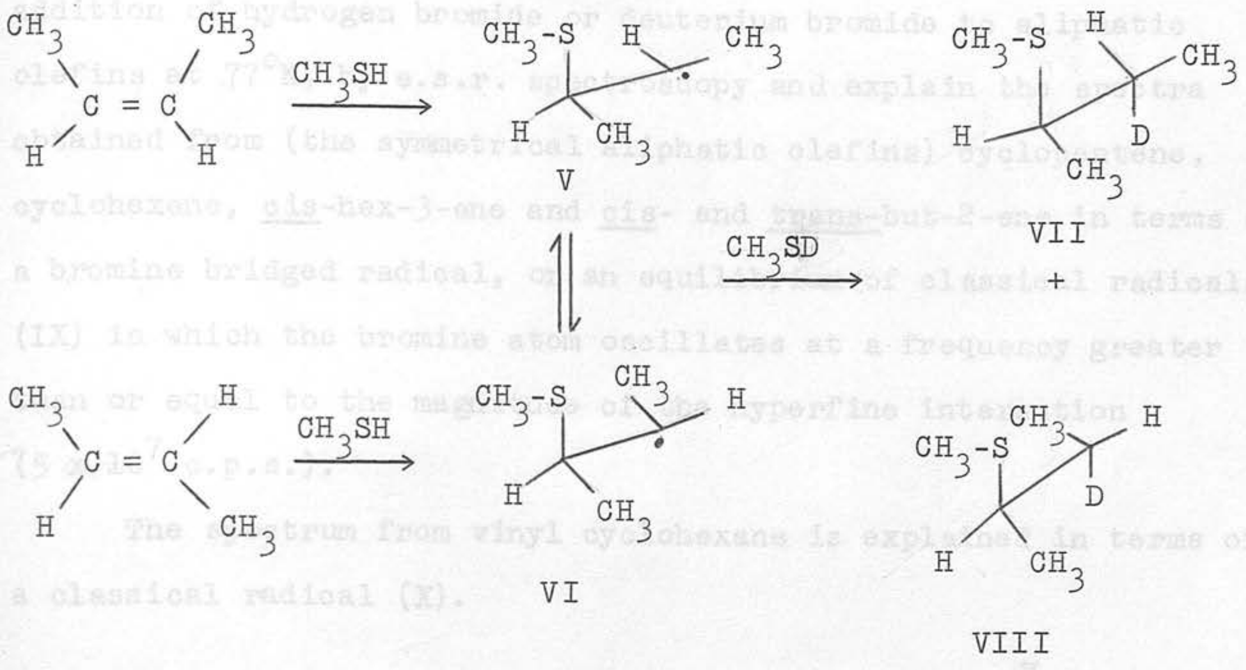
The light initiated irreversible addition[63] of bromotrichloromethane to both <u>cis</u>- and <u>trans</u>- but-2-ene at 0-25° yields the same mixture of products and is attributed to an equilibrium of diastereoisomeric radicals being set up rapidly before displacement with addendum can occur. (cf. scheme (V) $\rightleftharpoons$ (VI) for the addition of methane thiol).

The addition of bromotrichloromethane to cis- and trans-stilbene to give the same product,[64] assumed to be the thermodynamically more stable erythro isomer, can be explained similarly.

The stereochemistry of the addition of sulphur containing compounds to olefins has been investigated and reviewed.[65] Free radical thiol additions are generally less stereoselective than the additions of hydrogen bromide and additions to cyclic systems (except bridged bicyclic) show a preference for trans addition although complete stereospecificity has not been reported. Examples are[66] the 94% trans addition of thiophenol to 1-chlorocyclohexene and the 70% trans addition of thiolacetic acid to 1-methylcyclohexene. cis addition is reduced by increasing the thiol:olefin ratio.

The stereochemical results are rationalised by a mechanism involving classical radicals with the lack of stereospecificity attributed to slow chain transfer steps, as in thiol additions a series of compounds which is less reactive as chain transfer agents than hydrogen bromide is encountered.

Methyl mercaptan[67] undergoes photoinitiated addition in a stereospecific trans manner to cis- and trans-2-butene in the presence of dueterium bromide whereas in the absence of this, the same isomeric mixture is obtained for both olefins.



In presence of DBr:- $V \xrightarrow{DBr} VII$

$VI \longrightarrow VIII$

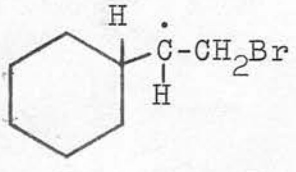
The above observations support the competitive theory as steric control arises from the rapid reaction of the diastereomerically related 3-methyl-2-butyl intermediate radicals (V) and (VI) with deuterium bromide before isomerisation can occur.

Various other addenda have been observed to add stereoselectively^{65} including dinitrogen tetroxide which adds to cyclohexene yielding 58% trans-2-nitrocyclohexyl nitrite and to cyclopentene to yield 84% trans-2-nitrocyclopentyl nitrite. Addition to 1-methylcyclohexene yielded stereospecifically 1-methyl-trans-2-nitrocyclohexyl nitrite and this is attributed to steric and conformational considerations in the classical intermediate radical.

Abell and Piette[68] have recently studied the photoinduced addition of hydrogen bromide or deuterium bromide to aliphatic olefins at 77°K, by e.s.r. spectroscopy and explain the spectra obtained from (the symmetrical aliphatic olefins) cyclopentene, cyclohexene, cis-hex-3-ene and cis- and trans-but-2-ene in terms of a bromine bridged radical, or an equilibrium of classical radicals (IX) in which the bromine atom oscillates at a frequency greater than or equal to the magnitude of the hyperfine interaction (5 x 10^7 c.p.s.).

The spectrum from vinyl cyclohexane is explained in terms of a classical radical (X).

$$\mathrm{R\dot{C}H-\underset{\underset{Br}{|}}{C}HR \rightleftharpoons R\underset{\underset{Br}{|}}{C}H-C\dot{H}R}$$

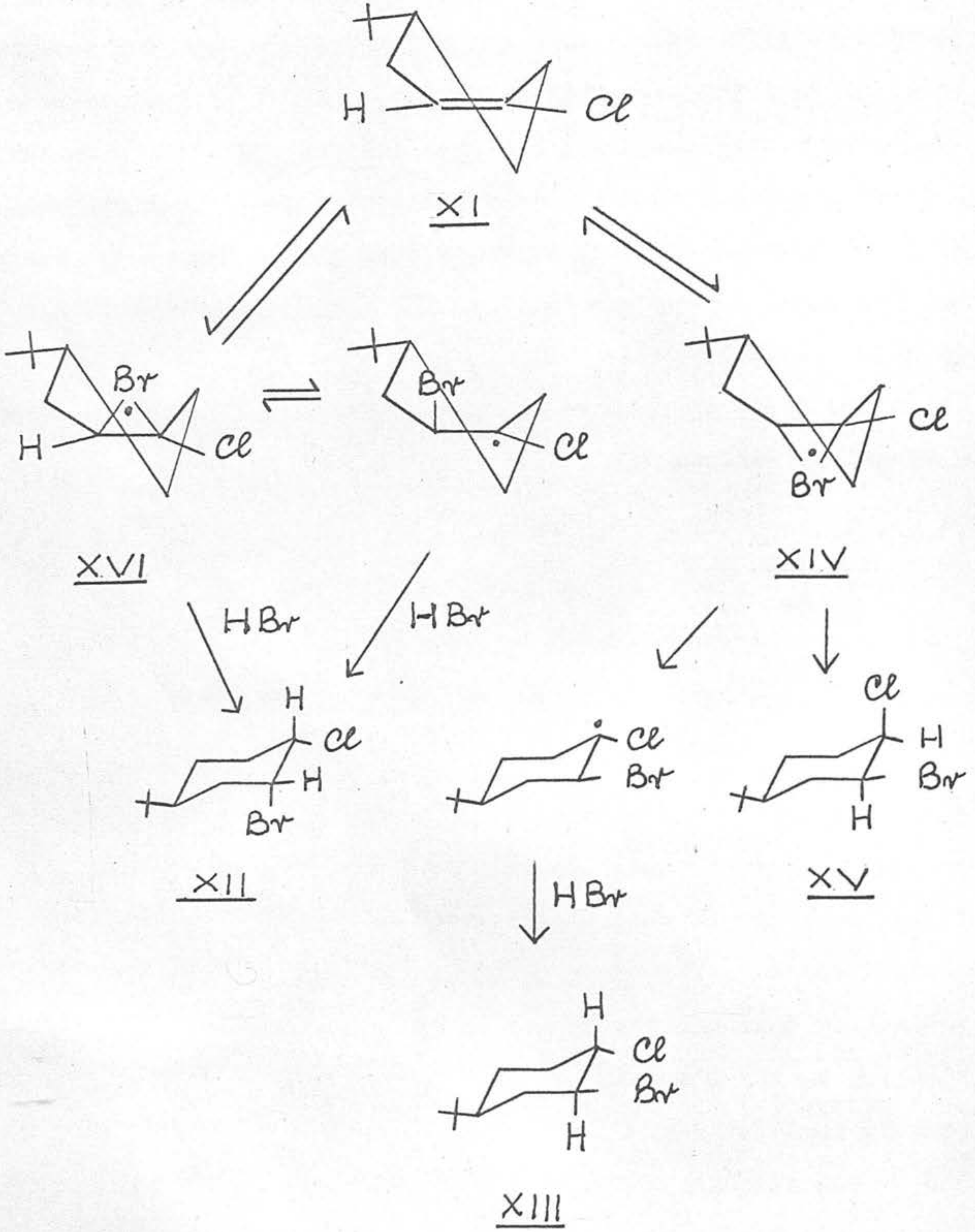


IX

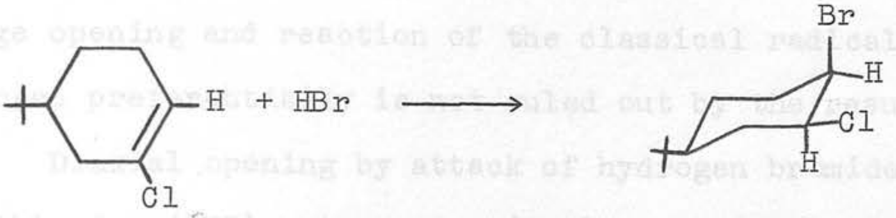
X

In the solid state, the addition of hydrogen atoms should also be possible and in view of this and theoretical factors, Symons[69] considers that the spectra arise from allyl radicals formed by hydrogen abstraction from the olefins, and not from bridged radicals formed by addition of bromine. It must also be remembered that results in the solid phase need not bear any relation to the situation in the liquid phase at the more usual working temperatures.

Radical chain additions to substituted cyclohexenes of known fixed conformation have recently been investigated.


H
Cl
XI
Br
H
Cl
XVI
Br
Cl
Br
Cl
XIV
HBr
HBr
H
Cl
H
Br
XII
Cl
Br
Cl
H
Br
H
XV
HBr
H
Cl
Br
H
XIII

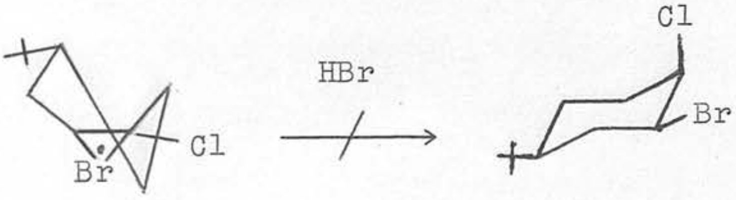
The addition[62a] of hydrogen bromide to 2-chloro-4-t-butylcyclohexene gives a single product, <u>cis</u>-3-chloro-<u>cis</u>-4-bromo-t-butylcyclohexane.



The addition[62] of hydrogen bromide at -78° in pentane to 1-chloro-4-t-butyl cyclohexene (XI) results in 95-98% diaxial addition to produce <u>trans</u>-3-bromo-<u>trans</u>-4-chloro-t-butylcyclohexane (XII) and the formation of a small amount (<u>ca</u>. 5%) of <u>cis</u>-3-bromo-<u>trans</u>-4-chloro-t-butylcyclohexane (XIII). In these cases it is necessary to explain why bromine atoms appear to attack almost exclusively on one side of the double bond when the equatorial t-butyl group does not significantly shield either side. Skell and Readio[62] propose that the formation of the minor adduct (XIII) results from initial bromine bridging on the side of the double bond <u>cis</u> to the t-butyl group. The transfer of a hydrogen atom to this bridged form (XIV) would give <u>cis</u>-3-bromo-<u>cis</u>-4-chloro-t-butylcyclohexane (XV). The fact that (XV) is not detected is explained by the bridged form opening to a classical radical and the product (XIII) resulting from accessibility of hydrogen bromide approach and product stability which both influence the hydrogen abstraction to occur preferentially to the axial position.

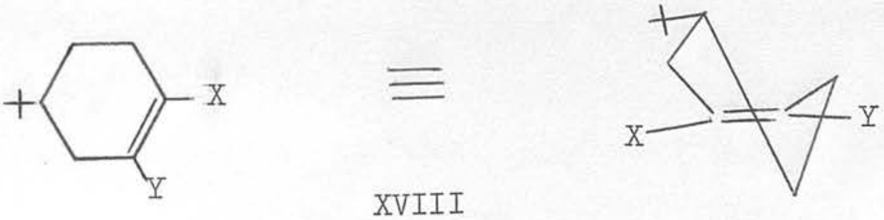
Formation of the major adduct (XII) requires initial bridging of bromine on the side of the double bond trans to the t-butyl group. Reaction to abstract hydrogen then occurs rapidly with the bridged intermediate (XVI). However, the alternative process of bridge opening and reaction of the classical radical to give axial hydrogen preferentially is not ruled out by the results.

Diaxial opening by attack of hydrogen bromide at C-4 is possible for (XVI) but not for (XIV). If (XIV) did react it would produce (XVII), a compound not observed. For (XIV), the lower energy path is ring opening to the classical radical.



XIV XVII

Similar results (Table I) have been obtained in the additions of methanethiol and thiolacetic acid to the substituted cyclohexenes (XVIII).



XVIII

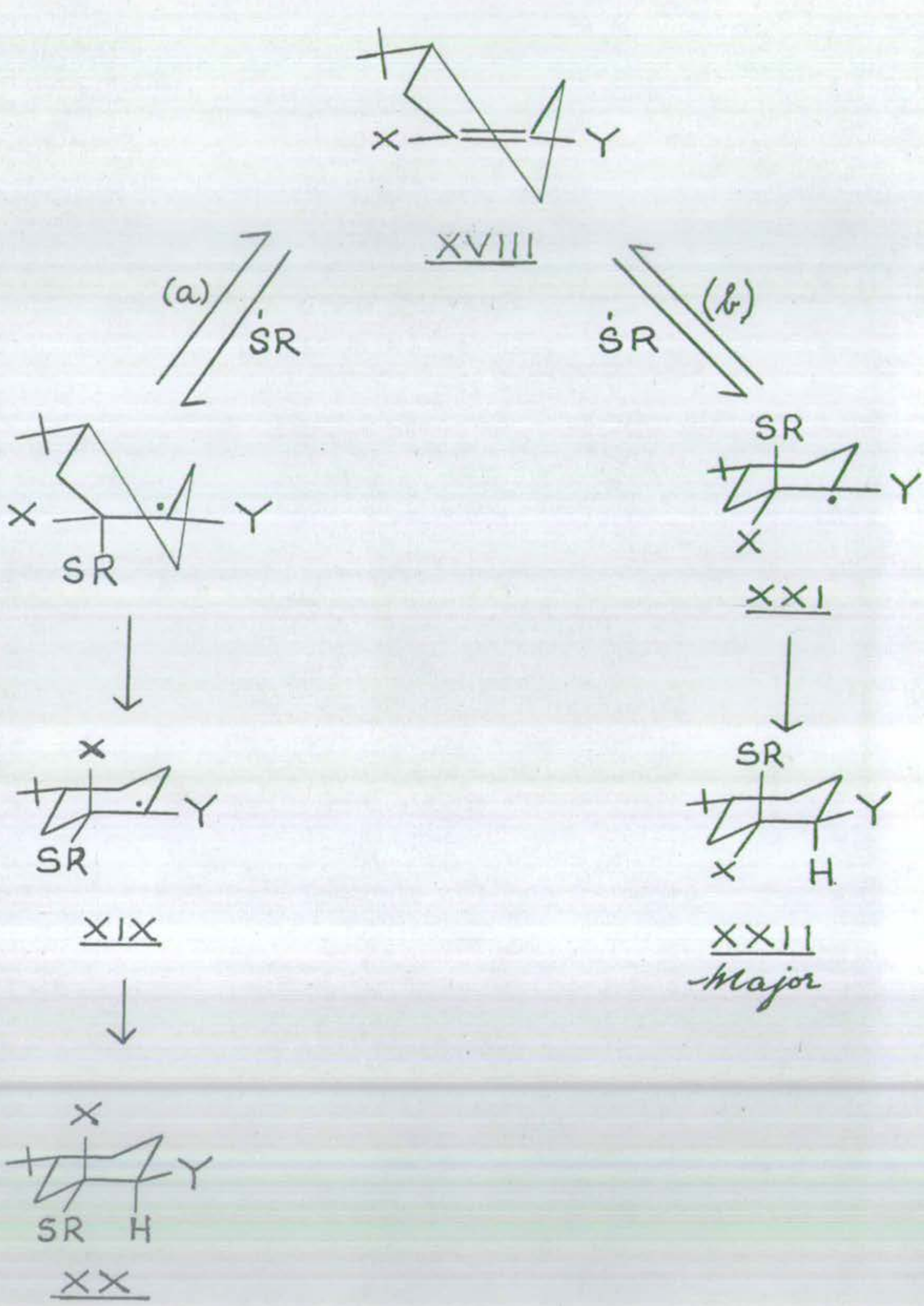

X
Y
XVIII
(a)
ṠR
(b)
ṠR
X
Y
SR
SR
Y
X
XXI
X
Y
SR
XIX
SR
Y
X
H
XXII
Major
X
Y
SR
H
XX

Table I. Addition of RSH to 1,2-substituted-4-t-butylcyclohexenes

R	X	Y	Temp.	Initiator	Ref.
Me	H	Cl	-78	hν	70
AcO	H	Me	Various*	hν	71
Me	H	H	"	hν	72
AcO	Cl	H	"	AIBN	73

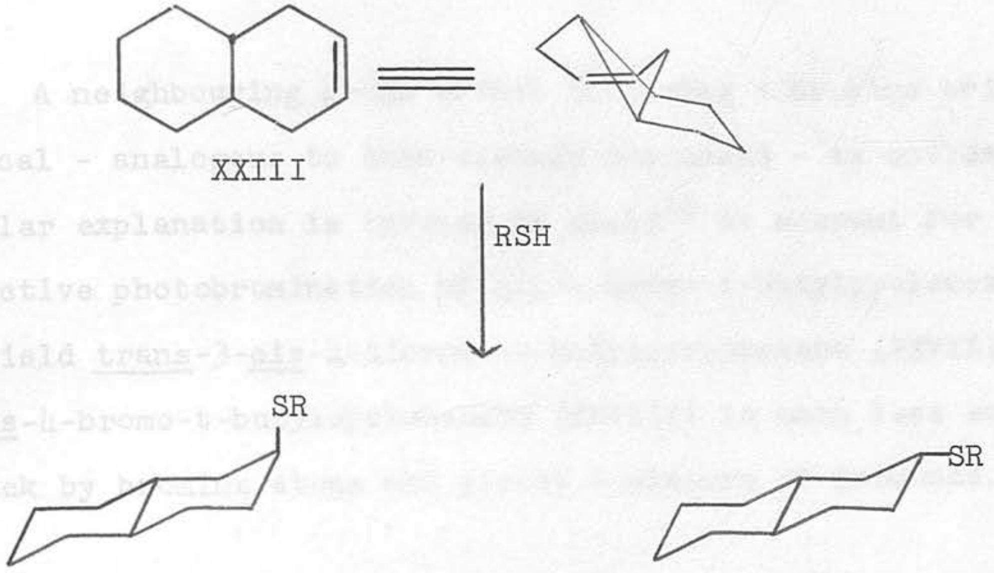
* The temperatures employed ranged between -70° and 100°. The slight differences observed in product isomer ratios within this range were within experimental error.

In all cases, the predominant product was the less stable axially substituted isomer (XXII) arising from trans addition of RSH. Skell rationalises this observation by an analogous mechanism to that proposed for the addition of hydrogen bromide to the same system, namely, a bridged sulphur intermediate radical.

The other authors, assuming that the attacking RS• radical approaches perpendicularly the carbon-carbon double bond, a view already proposed[74] and supported by molecular orbital calculations,[75] suggest that the predominance of axial isomer (XXII) in the product arises from the intermediates involved in the alternative routes (a) and (b) for attack at C_2. (Similar routes are available for attack at C_1).

The radical (XIX) in route (a) in which the final product is the equatorial isomer (XX) assumes the twist-boat form which is conformationally less stable than the chair form intermediate (XXI) involved in path (b). Hence, (b) is the preferred route - resulting in predominance of axial product (XXII). The hydrogen bromide addition discussed above may be explained in the same way.

Similar conformational factors are also proposed[76] to account for the predominant formation of the axial isomer (XXIV) in the light induced addition of mercaptans to trans-Δ^2-octalin (XXIII) at 40°.



XXIV

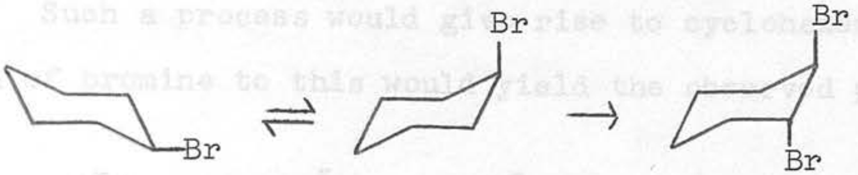
XXV

R = Me or Et.

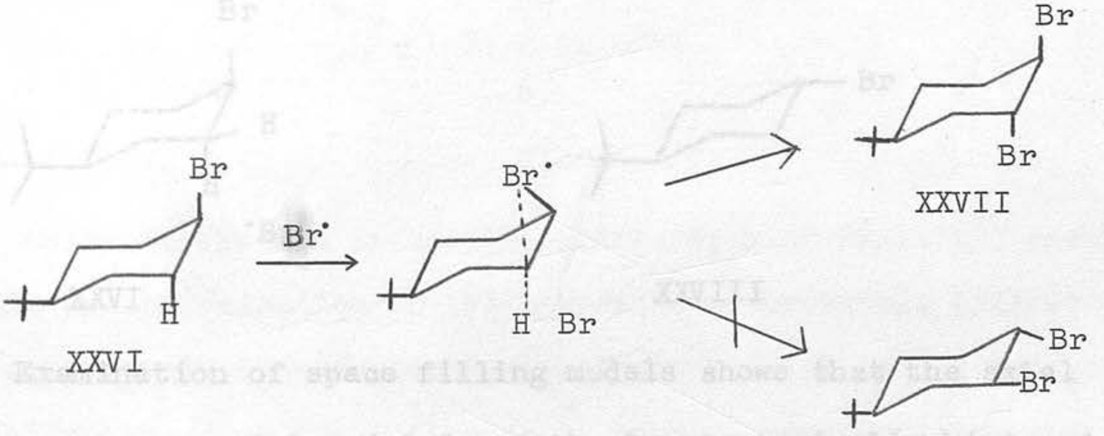
Thus, stereoisomeric preferences in radical additions to cyclohexenes can be explained on the basis of conformational factors and it is not necessary to postulate the formation of bridged intermediate radicals.

1.3. Halogenation of substituted alkanes.

The photobromination[77] of alkyl bromides is highly selective, giving 84-94% of the vicinal dibromide isomer. In the case of bromocyclohexane, the trans-1-2-dibromocyclohexane is the major product.



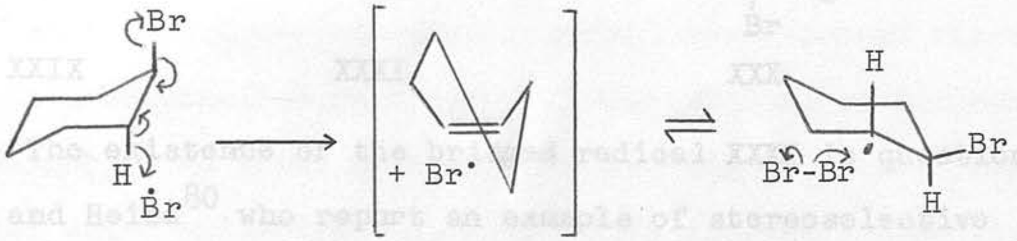
A neighbouring group effect involving a bromine bridged radical - analogous to that already discussed - is envisaged; a similar explanation is invoked by Skell[78] to account for the highly selective photobromination of cis-4-bromo-t-butylcyclohexane (XXVI) to yield trans-3-cis-4-dibromo-t-butylcyclohexane (XXVII). The trans-4-bromo-t-butylcyclohexane (XXVIII) is much less selective to attack by bromine atoms and yields a mixture of products.


XXVI

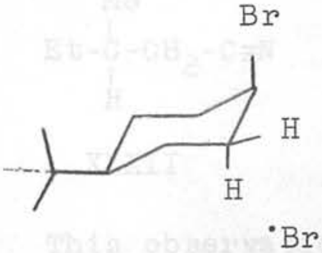
XXVII

The attack of bromine on the bridged radical is envisaged as taking place at C-3 and not at C-4 as in the latter case a boat-form transition state would be required. Attack at C-3 follows the lower energy path maintaining the more stable chair form in the transition state, leading to the diaxial product.

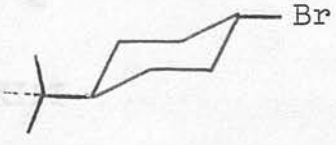
In both cases, alternative explanations are available. The possibility that a concerted process is taking place has been overlooked. Such a process would give rise to cyclohexene and re-addition of bromine to this would yield the observed product.



In the case of the t-butylcyclohexanes the preferred substitution can also be explained on steric grounds.



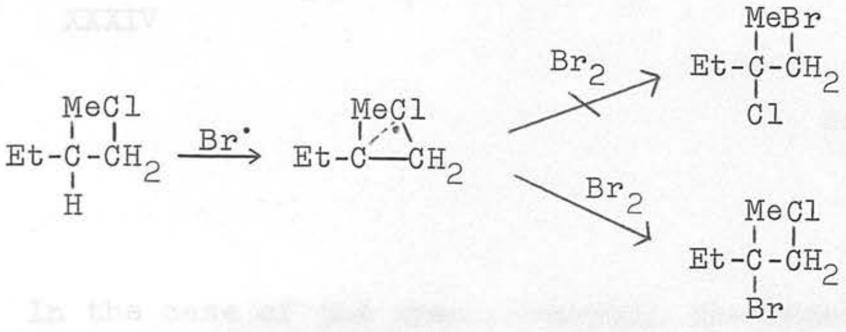
XXVI



XXVIII

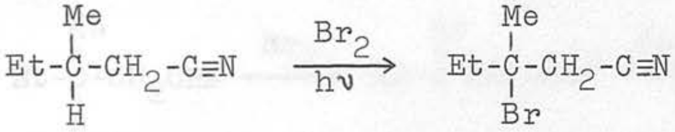
Examination of space filling models shows that the axial hydrogen atoms on C-3 and C-5 are the least sterically hindered in the cis compound (XXVI) whereas in the trans compound (XXVIII) all the hydrogen atoms are considerably hindered to bromine attack and in this case a variety of products results.

The photobromination[79] of (+)-2-methyl-1-chlorobutane (XXIX) is stereospecific to the (-)-1-chloro-2-bromo compound (XXX).



XXIX XXXI XXX

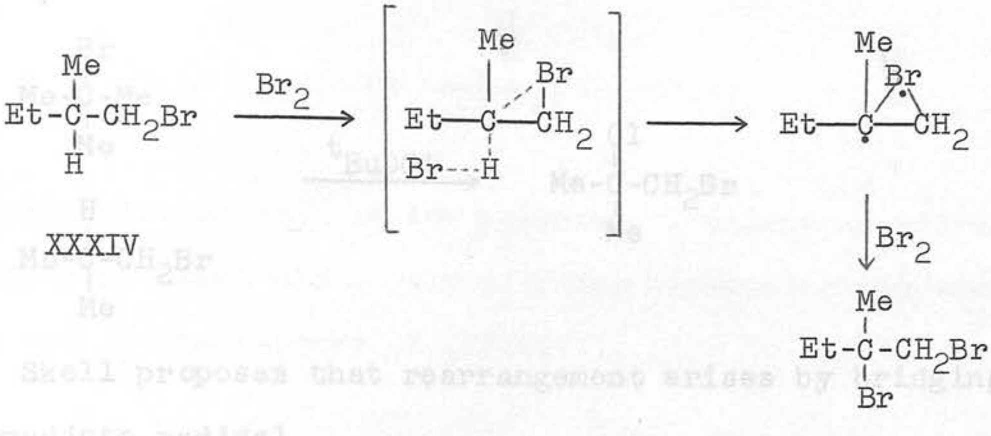
The existence of the bridged radical XXXI is questioned by Haag and Heiba[80] who report an example of stereoselective bromination in which bridged radicals cannot be intermediates, namely, the liquid phase photobromination of (+)-1-cyano-2-methylbutane (XXXII) which proceeds with high selectivity at the tertiary carbon to yield (+)-2-bromo-1-cyano-2-methylbutane (XXXIII)



$$\mathrm{Et}\text{-}\overset{\mathrm{Me}}{\underset{\mathrm{H}}{\mathrm{C}}}\text{-}\mathrm{CH_2}\text{-}\mathrm{C{\equiv}N} \xrightarrow[h\nu]{\mathrm{Br_2}} \mathrm{Et}\text{-}\overset{\mathrm{Me}}{\underset{\mathrm{Br}}{\mathrm{C}}}\text{-}\mathrm{CH_2}\text{-}\mathrm{C{\equiv}N}$$

XXXII XXXIII

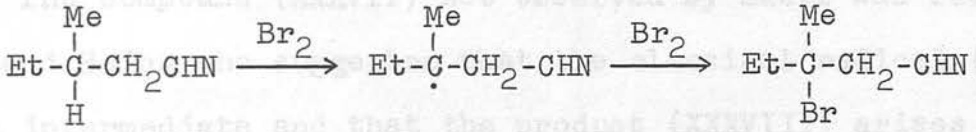
This observation is compared directly with Skell's[79] result for the photobromination of (+)-1-bromo-2-methylbutane (XXXIV) to give exclusively 1,2-dibromo-2-methylbutane (XXXV) via a bridged radical which under the influence of bromine concentration and temperature isomerises to an open chain from which racemises.



XXXIV

XXXV

In the case of the cyano compound, the observed stereoselective bromination rules out a planar radical as intermediate and neighbouring group participation leading to a cyano bridged radical seems unlikely. An alternative explanation involving short-lived non-planar radicals is envisaged, where the radical formed initially by hydrogen abstraction has a pyramidal configuration and chain transfer with bromine occurs before racemisation.

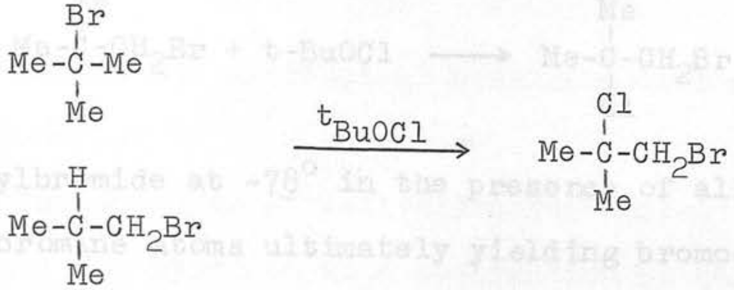


$$\mathrm{Et{-}\underset{H}{\overset{Me}{C}}{-}CH_2CHN \xrightarrow{Br_2} Et{-}\underset{\bullet}{\overset{Me}{C}}{-}CH_2{-}CHN \xrightarrow{Br_2} Et{-}\underset{Br}{\overset{Me}{C}}{-}CH_2{-}CHN}$$

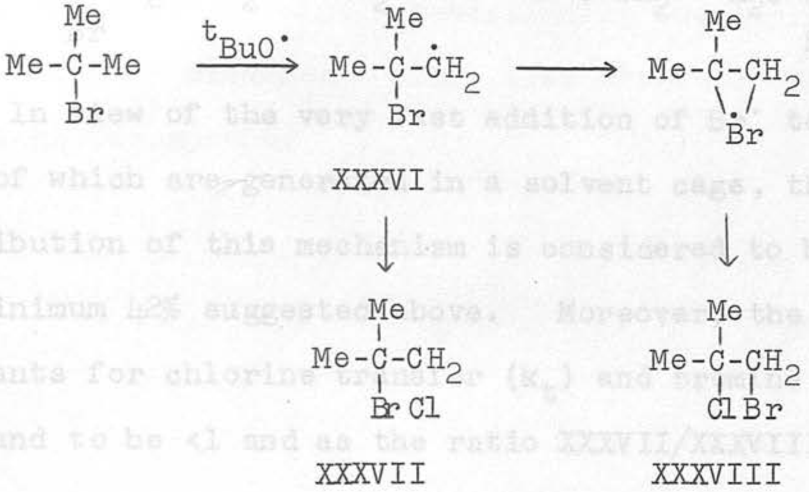
The same authors[81] re-examined the radical rearrangements investigated by Skell[82] <u>et al</u>. in which radical chain chlorination of i-propyl and n-propyl bromides with t-butylhypochlorite yield a common product, 1-bromo-2-chloropropane,

$$\left.\begin{array}{l}\mathrm{CH_3CH_2CH_2Br}\\ \mathrm{CH_3CHBrCH_3}\end{array}\right\}\xrightarrow{^{t}\mathrm{BuOCl}}\mathrm{CH_3CHClCH_2Br}$$

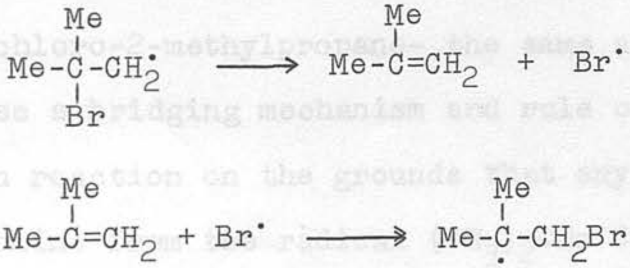
and i-butyl and t-butylbromides yield 1-bromo-2-chloro-2-methylpropane.

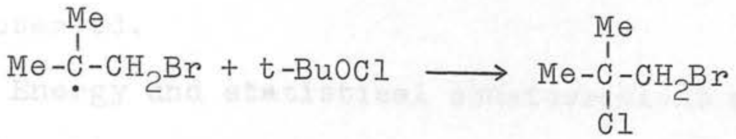


Skell proposes that rearrangement arises by bridging of the intermediate radical.



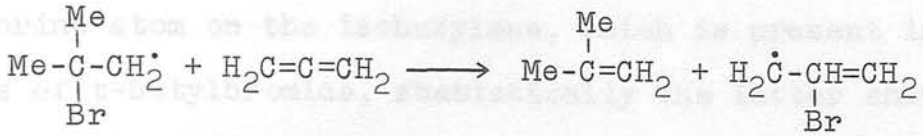
The compound (XXXVII) not observed by Skell was isolated by Haag and Heiba who suggested that the classical radical (XXXVI) is an intermediate and that the product (XXXVIII) arises at least in part from bromine atom elimination and re-addition to the double bond. This was supported by photochlorination of





$$\mathrm{Me{-}\overset{Me}{\underset{\bullet}{C}}{-}CH_2Br + t{-}BuOCl \longrightarrow Me{-}\overset{Me}{\underset{Cl}{C}}{-}CH_2Br}$$

t-butylbromide at -78° in the presence of allene as scavenger for free bromine atoms ultimately yielding bromochloropropenes in 42% yield at the expense of (XXXVIII).



$$\mathrm{Me{-}\overset{Me}{\underset{Br}{C}}{-}\dot{C}H_2 + H_2C{=}C{=}CH_2 \longrightarrow Me{-}\overset{Me}{C}{=}CH_2 + H_2\dot{C}{-}\underset{Br}{C}H{=}CH_2}$$

In view of the very fast addition of Br˙ to isobutylene, both of which are generated in a solvent cage, the actual contribution of this mechanism is considered to be greater than the minimum 42% suggested above. Moreover, the ratio of rate constants for chlorine transfer (k_t) and bromine elimination (k_d) is found to be <1 and as the ratio XXXVII/XXXVIII can be expressed as:-

$$\mathrm{XXXVII}/_{\mathrm{XXXVIII}} = {}^{k_t}/_{k_d}\,[\mathrm{t{-}BuOCl}]$$

the preferred route is elimination (with concomitant re-addition to give the observed product).

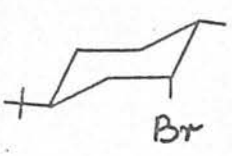
Juneja and Hodnett[83] photochlorinated t-butyl bromide at 24° in carbon tetrachloride and observed only one product, namely, 1-bromo-2-chloro-2-methylpropane- the same as that found by Skell. They propose a bridging mechanism and rule out the elimination and re-addition reaction on the grounds that any isobutylene formed by loss of bromine from the radical $(CH_3)_2CBr{\cdot}CH_2$ would add a molecule of chlorine very quickly to form the dichloro-compound, none of which was observed.

Energy and statistical considerations make this argument questionable.

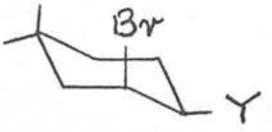
The energies of activation for chlorine addition to a double bond and for hydrogen atom abstraction by chlorine are very small and similar. Therefore, as chlorine addition requires attack of a chlorine atom on the isobutylene, which is present in a large excess of t-butylbromide, statistically the latter should be preferentially attacked. This also accounts for the absence of the dichlorocompound.

SECTION 2

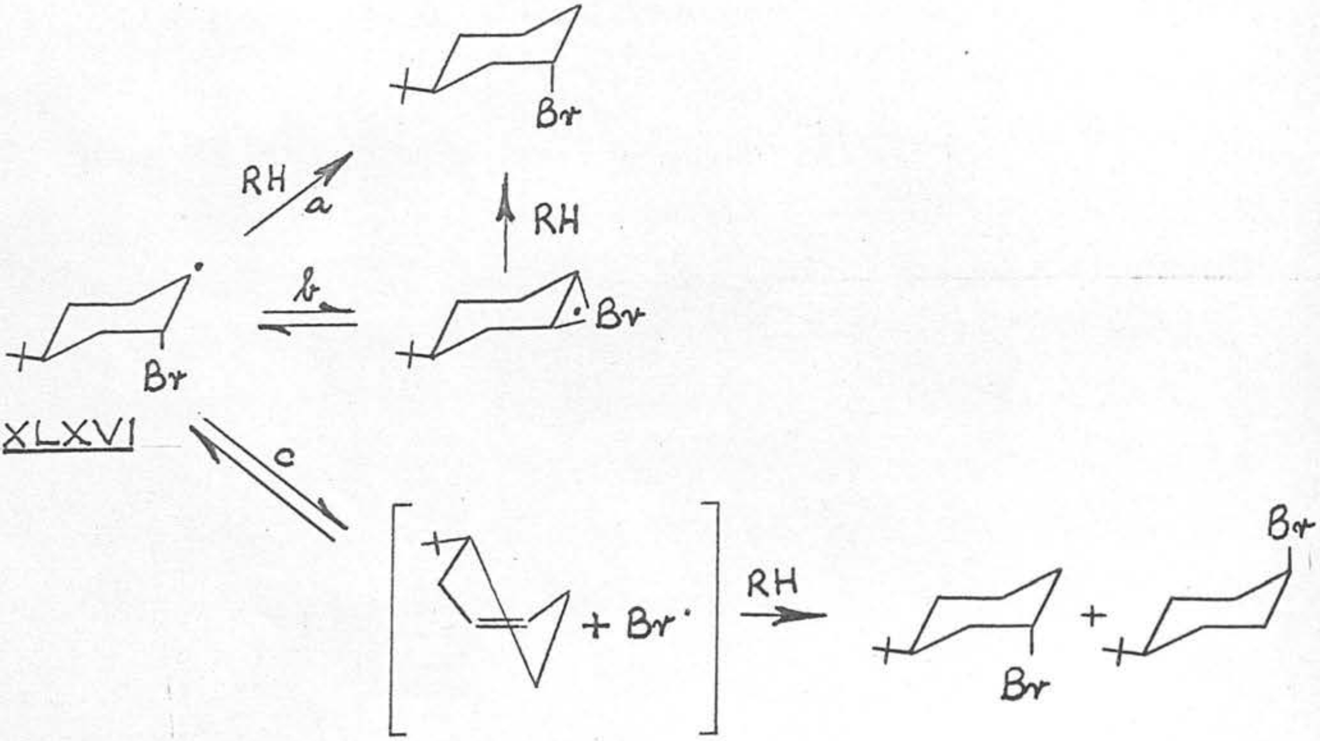
Discussion

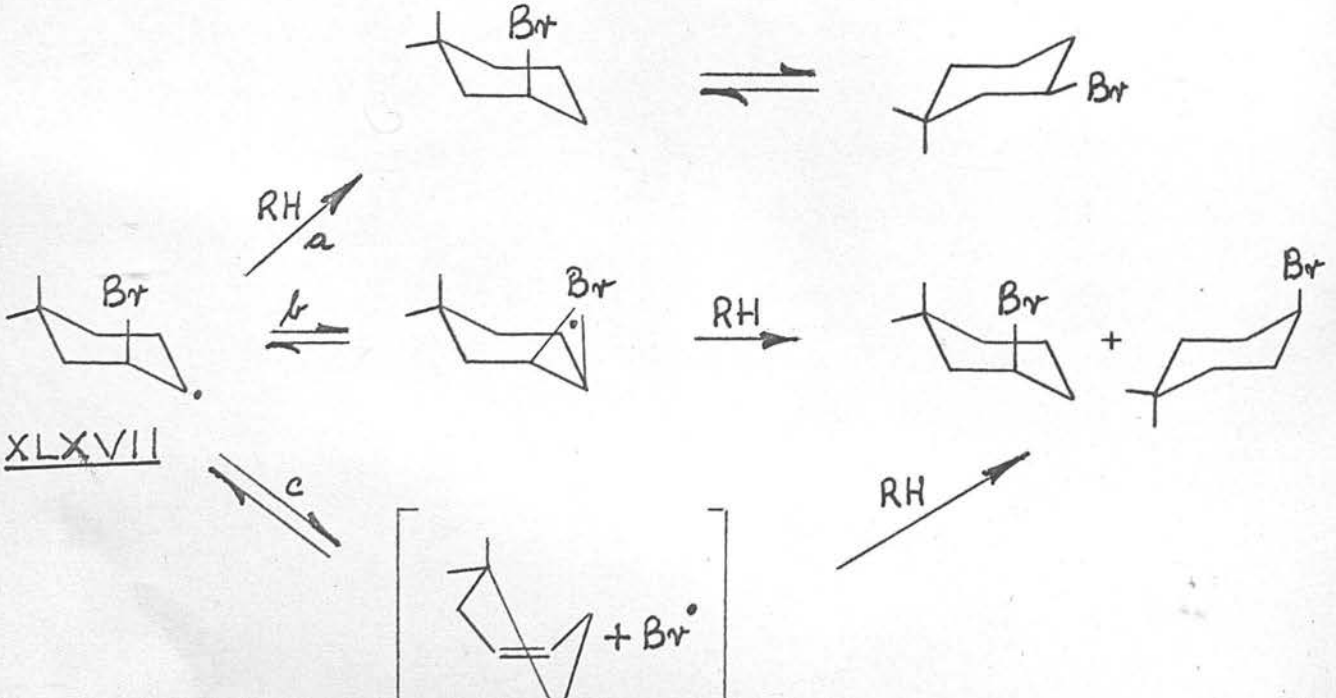

Y
Br

XXXIX


Br
Y

XL


Br
RH
a
RH
b
Br
Br
XLXVI
c
+ Br·
RH
Br
Br
+


Br
Br
RH
a
Br
b
Br
RH
Br
Br
+
XLXVII
c
RH
+ Br·

2.1. The object of the research

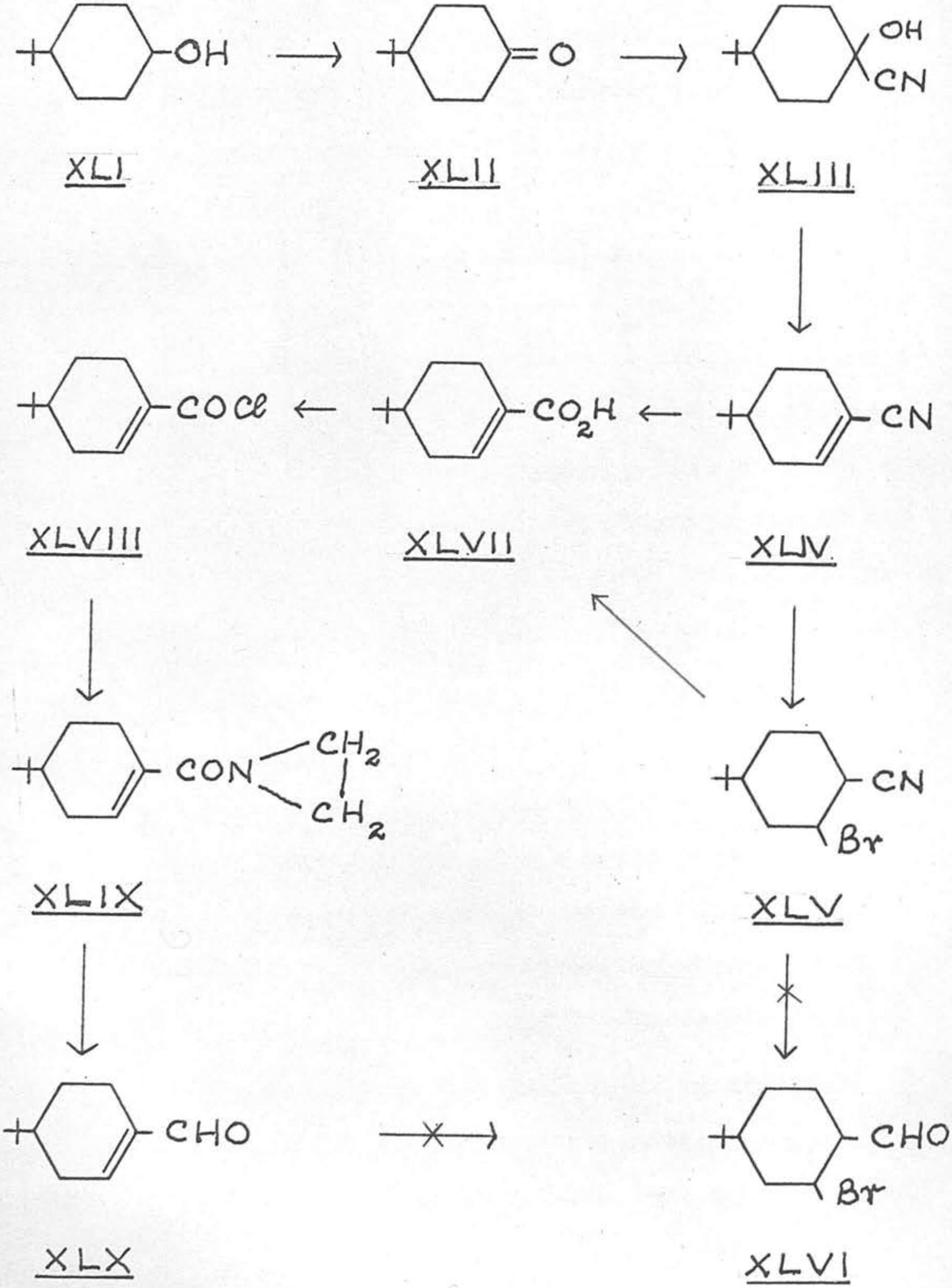
Since the information available concerning the existence, or otherwise, of bridged free radicals is, in the majority of cases, not clear cut, it seemed worthwhile to investigate the possibility of synthesising systems designed to distinguish between the formation of classical or bridged radicals on the basis of reaction products.

The compounds (XXXIX) and (XL) opposite, (where Y = -CHO, -N=N-, or $-CO_2-CO_2-$) should give rise to the radicals (XLXVI) and (XLXVII) respectively under the appropriate conditions. Three pathways are available for the formation of the bromohydrocarbons by reaction with a hydrogen donor RH:

(a) Direct hydrogen abstraction from RH by a classical radical leading in each case to a single product, either trans-3-t-butyl-1-bromocyclohexane or 3,3-dimethyl-1-bromocyclohexane.

(b) The formation of a bridged free radical which opens diaxially upon reaction with RH. This would yield a single product trans-3-t-butyl-1-bromocyclohexane from radical (XLXVI) since the conformation is fixed by the t-butyl group. In the case of (XLXVII), two products, 3,3-dimethyl-1-bromocyclohexane and 4,4-dimethyl-1-bromocyclohexane would arise since diaxial opening may occur at either position.

(c) Elimination of bromine followed by re-addition at either end of the cyclohexene so produced, followed by hydrogen transfer with RH. This process would result in the formation of two products in both cases.


OH
O
OH
CN
XLI
XLII
XLIII
COCl
CO_2H
CN
XLVIII
XLVII
XLIV
CON
CH_2
CH_2
CN
Br
XLIX
XLV
CHO
CHO
Br
XLX
XLVI

Thus, a study of the reaction products should indicate the reaction pathway and therefore attention was directed towards the synthesis of the compounds (XXXIX) and (XL) and methods of identifying, separating and estimating the possible reaction products, the alkyl bromocyclohexanes.

2.2. The attempted syntheses of trans-4,4'-di-t-butyl-cis-2,2'-dibromoazocyclohexane and trans-4-t-butyl-cis-2-bromocyclohexane-1-carboxaldehyde.

The system (XXXIX) was studied first as the information gained from it would dictate the subsequent course of the investigation; i.e. if two products are formed in the final reaction, then path (c) operates and the investigation of the system (XL) would yield no further information on bridging.

It is important that the bromine in (XXXIX) be axial to facilitate bridging. 4-t-butyl-2-bromocyclohexanone synthesised by the method of Allinger[84] is known to have the bromine in this position. However, treatment of the axial bromo-ketone so prepared, with hydrazine hydrate in an attempt to form the corresponding azine consistently resulted in the formation of tars. This precluded the reduction of the azine to the hydrazine with lithium aluminium hydride and subsequent oxidation of this with mercuric chloride to yield the azo compound.

The scheme opposite summarises attempted syntheses of 4-t-butyl-2-bromocyclohexane-1-carboxaldehyde (XLVI). 4-t-butylcyclohexanol (XLI) was oxidised with sodium dichromate and glacial acetic acid in the presence of benzene to extract the organic material. Treatment of the purified ketone (XLII) with potassium cyanide and hydrochloric acid yielded the cyanohydrin (XLIII) which was not isolated but immediately dehydrated, by boiling with thionyl chloride in benzene solution, to give the unsaturated nitrile, 4-t-butyl-1-cyanocyclohexene (XLIV). Systematic variation of the experimental conditions indicated an optimum yield of (XLIV) after *ca.*, 60 hours boiling. Insufficient dehydration resulted in regeneration of the ketone during the work up.

The nitrile was isolated and purified before the ultra-violet catalysed addition of hydrogen bromide at -78° in n-hexane solution. The structure of the product from this stage, *trans*-4-t-butyl-*cis*-2-bromo-1-cyanocyclohexane (XLV) was verified by n.m.r. spectroscopy and the reaction is discussed in more detail in section 2.3.

The final stage of this route, namely reduction by the inverse addition of lithium aluminium hydride to an ethereal solution of the nitrile (XLV) was attempted using both a solution and a suspension of the reagent in ether. In both cases the starting material was recovered unchanged. A similar result was obtained using lithium triethoxyaluminohydride.

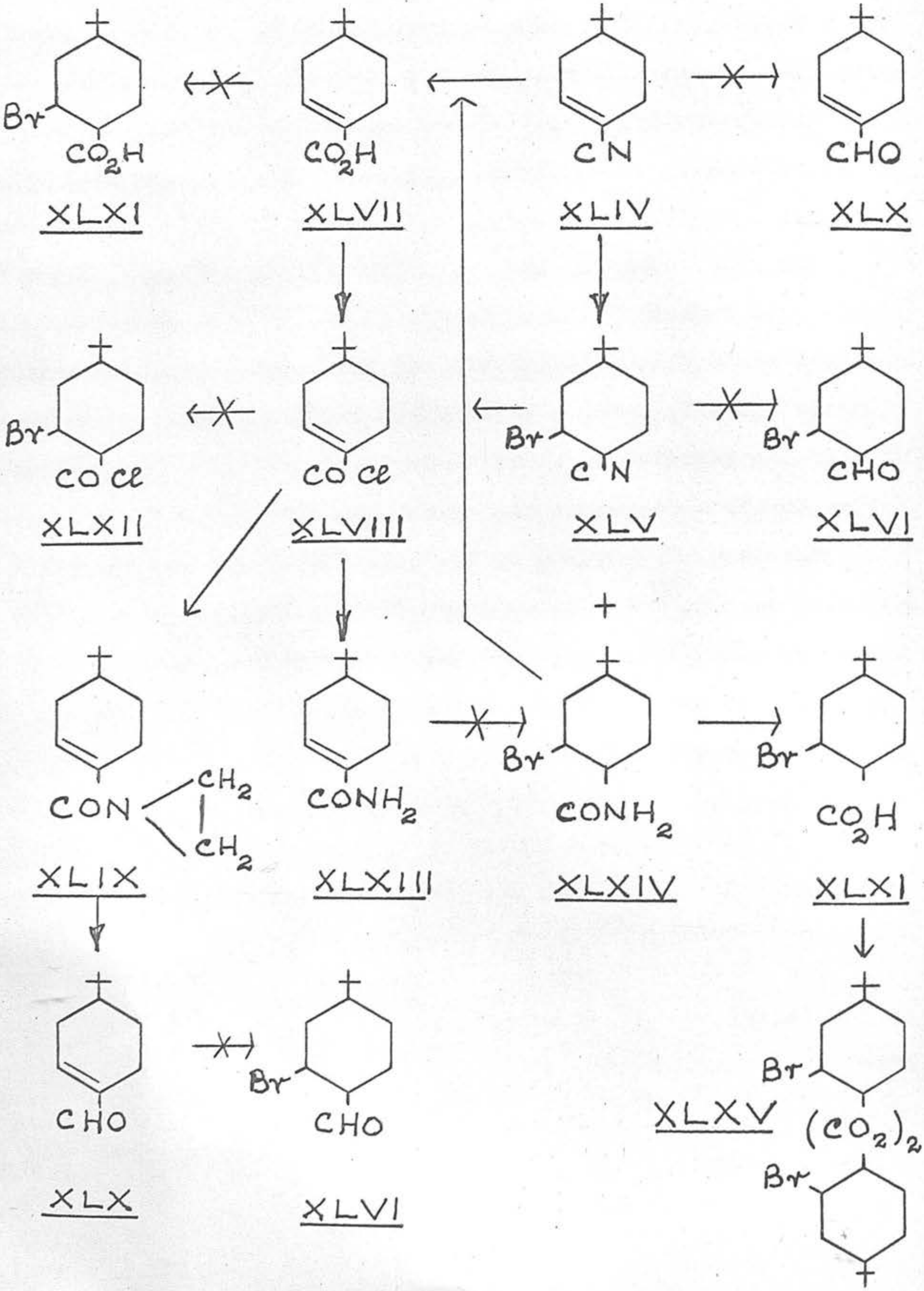
The reaction of the unsaturated nitrile (XLIV) with lithium aluminium hydride gave the same result, however, 4-t-butylcyclohexene-1-carboxaldehyde (XLX) was prepared from the nitrile by hydrolysis to the acid (XLVII). Treatment of this with thionyl chloride gave 4-t-butylcyclohexene-1-carbonyl chloride (XLVIII) which with ethyleneimine and triethylamine gave the intermediate substituted aziridine (XLIX). This was reduced to the aldehyde with a suspension of lithium aluminium hydride in ether. Equimolar quantities of the aziridine and the reducing agent kept the formation of the by-product of the reaction, 4-t-butyl-1-hydroxymethylcyclohexene to a minimum (ca., 10%) and gave the best yield of (XLX).

The final stage of this route proved impossible. The addition of hydrogen bromide to the aldehyde (XLX) and also to 4-t-butylcyclohexene-1-carboxylic acid (XLVII) and 4-t-butylcyclohexene-1-carbonyl chloride (XLVIII) under a variety of conditions resulted in recovery of starting material in every case, thus ruling out alternative routes to the aldehyde as summarised opposite.

The lack of addition to the acid was unexpected as crotonic acid is reported[85] to add hydrogen bromide satisfactorily. Moreover, the expected adduct, trans-4-t-butyl-cis-2-bromocyclohexane-1-carboxylic acid was obtained later by the mild hydrolysis of the corresponding amide.

2.3. The addition of hydrogen bromide to 4-t-butyl-1-cyanocyclohexene; 4,4-dimethyl-1-cyanocyclohexene and 4-t-butylcyclohexene

The addition of hydrogen bromide to 4-t-butyl-1-cyanocyclohexene (XLIV) at -78° in n-hexane solution yielded 4-t-butyl-2-bromo-1-cyanocyclohexane (XLV) as the major product under anhydrous conditions. However, on one occasion, 4-t-butyl-2-bromocyclohexane-1-carboxamide (XLXIV) was the major product suggesting that



Br
CO2H
XLXI
CO2H
XLVII
CN
XLIV
CHO
XLX
Br
CO Cl
XLXII
CO Cl
XLVIII
Br
CN
XLV
Br
CHO
XLVI
+
CON
CH2
CH2
XLIX
CONH2
XLXIII
Br
CONH2
XLXIV
Br
CO2H
XLXI
CHO
XLX
Br
CHO
XLVI
Br
XLXV
(CO2)2
Br

the introduction of water after the addition had taken place would result in a good yield of the amide. This was found to be the case. The reaction was thus used as a preparation of both compounds depending on the conditions. That the amide was formed after the addition was verified by the observation that hydrogen bromide would not add under these (or any other) conditions to 4-t-butylcyclohexene-1-carboxamide. The volume of water added was found to be critical as too little resulted in a smaller yield of amide whereas larger volumes resulted in a mixture of the amide, the nitrile and the unsaturated acid, 4-t-butylcyclohexene-1-carboxylic acid (XLVII); the latter being formed by hydrolysis of the nitrile by the aqueous acid mixture.

In separate experiments, the compounds, 4-t-butyl-1-cyanocyclohexene; 4-t-butyl-2-bromo-1-cyanocyclohexane and the amide (XLXIV) all gave the unsaturated acid (XLVII) on hydrolysis with 50% (v/v) sulphuric acid. Lower concentrations of the sulphuric acid did not effect reaction. The structures of the adduct (XLV) and the amide (XLXIV) were assigned by n.m.r. spectroscopy. The spectra are illustrated in figures (i) and (ii) and can be compared with that obtained by Skell[62] for <u>trans</u>-4-t-butyl-<u>cis</u>-2-bromo-1-chlorocyclohexane.

The equatorial hydrogen on C_2 in this compound has a signal at $5{\cdot}4\,\tau$ whereas that for the axial hydrogen on the same carbon in <u>trans</u>-4-t-butyl-<u>trans</u>-2-bromo-1-chlorocyclohexane is at $6{\cdot}3\,\tau$, which is in keeping with the observation[86] that an axial hydrogen absorption occurs at a higher field than that of an equatorial

Fig (1)

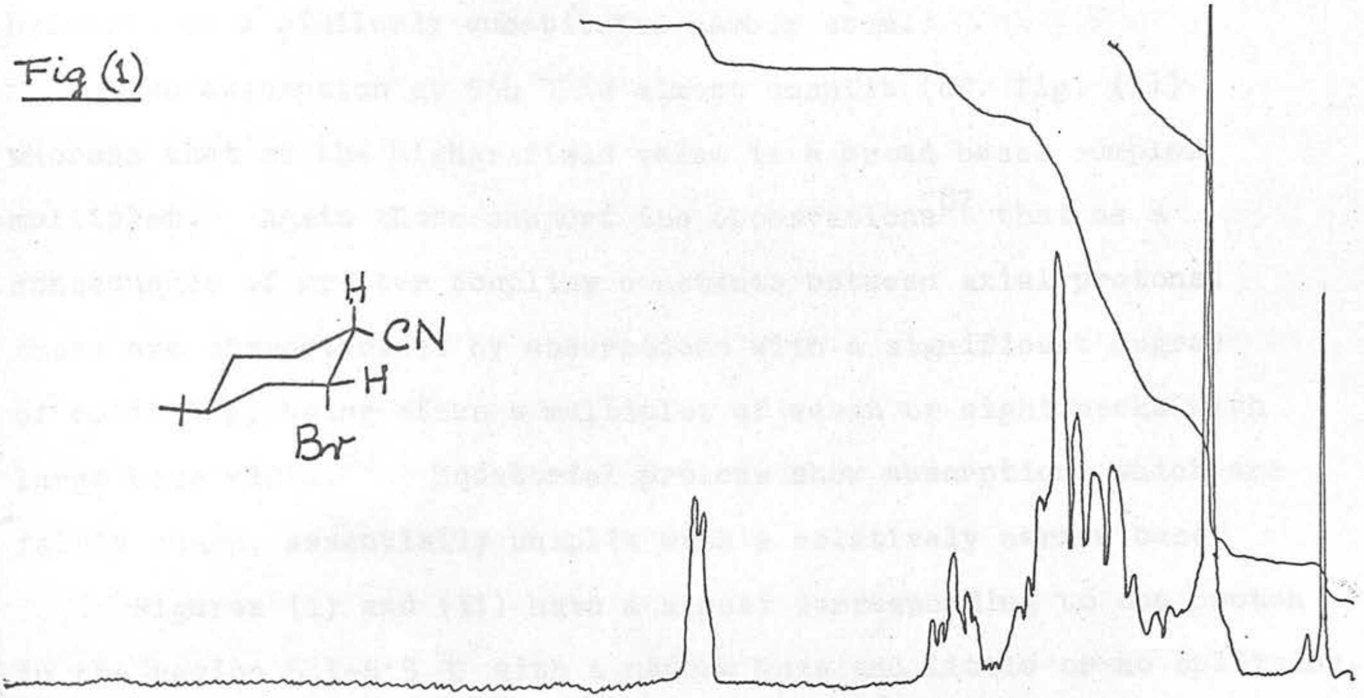
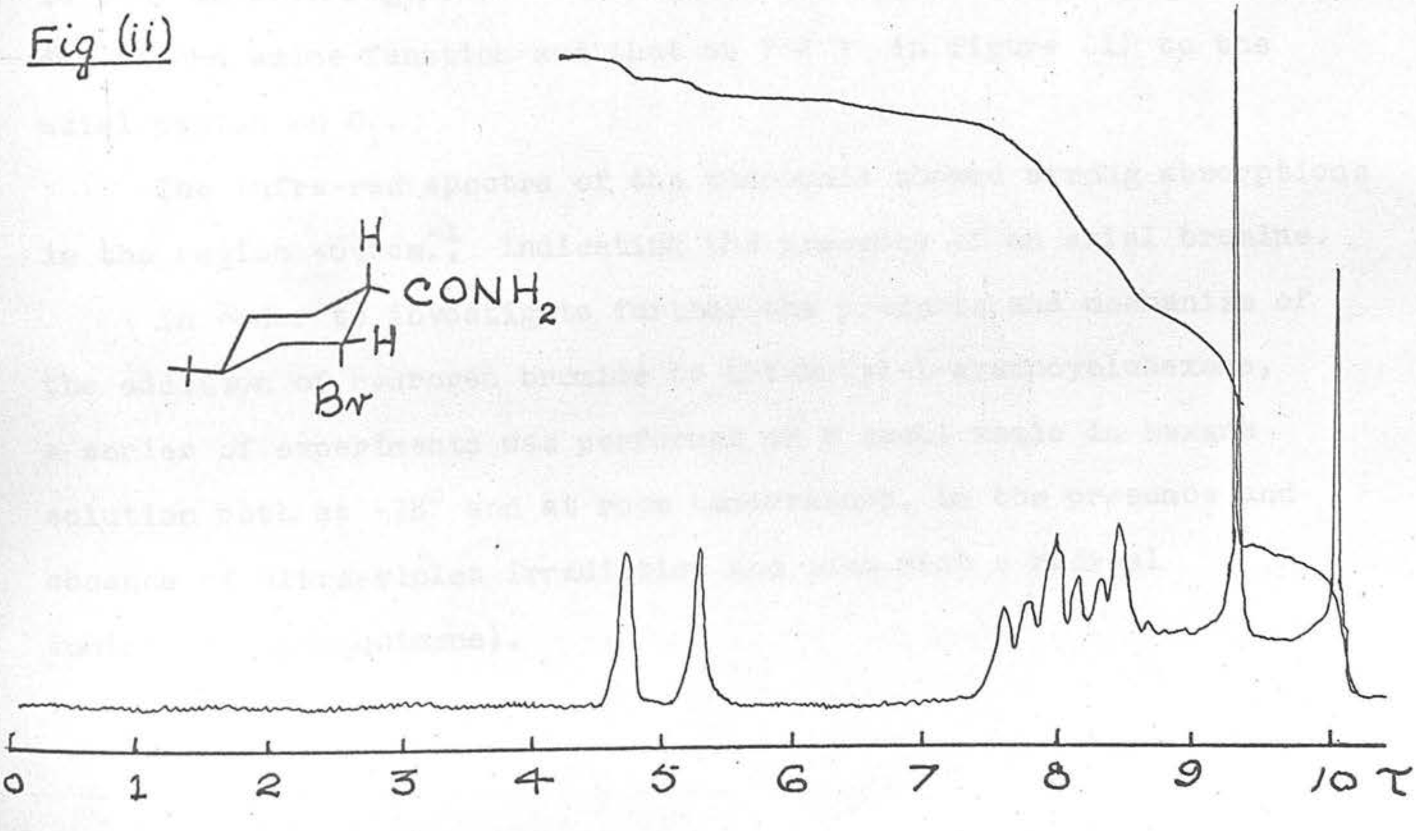


Fig (ii)



hydrogen on a similarly substituted carbon atom.

The absorption at 5·4 τ is almost unsplit (cf. fig. (i)) whereas that at the higher field value is a broad based complex multiplet. Again these support the observations[87] that as a consequence of greater coupling constants between axial protons, these are characterised by absorptions with a significant degree of splitting, being often a multiplet of seven or eight peaks with large base width.[88] Equatorial protons show absorptions which are fairly sharp, essentially unsplit with a relatively narrow base.

Figures (i) and (ii) have a signal corresponding to one proton in the region 5·1-5·5 τ with a narrow base and little or no splitting. The structures of the compounds have been assigned on the basis that this is due to an equatorial hydrogen on C_2.

The remaining peaks in the spectra are due to the t-butyl group at 9·3 τ and the reference standard tetramethylsilane at 10·0 τ in both figures. The peak at 4·7 τ in figure (ii) is due to the amine function and that at 7·2 τ in figure (i) to the axial proton on C_1.

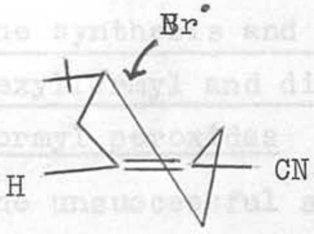
The infra-red spectra of the compounds showed strong absorptions in the region <690cm.$^{-1}$, indicating the presence of an axial bromine.

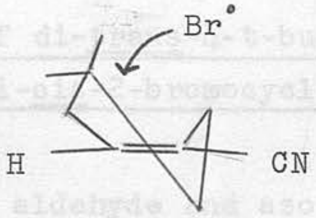
In order to investigate further the products and mechanism of the addition of hydrogen bromide to 4-t-butyl-1-cyanocyclohexene, a series of experiments was performed on a small scale in hexane solution both at -78° and at room temperature, in the presence and absence of ultra-violet irradiation and also with a radical inhibitor (hydroquinone).

The yield of adduct (XLV) was found to vary significantly with conditions; the greatest yield (78%) being achieved under similar conditions to those of the preparative scale reaction, i.e., ultra-violet irradiation at -78° under free radical conditions.

The results in the absence of ultra-violet and in the presence of an inhibitor at room temperature and -78° indicated that the adduct is also formed via an ionic pathway although the yield is very much less. However, it is noteworthy that the axially substituted isomer is the preferred product both by the free radical and ionic pathways. If this is rationalised by a mechanism involving a bromine bridge (<u>cf</u>. Skell) then the addition of the negatively charged bromide ion would also require a bridge.

The alternative explanation involving the perpendicular approach of the bromine atom to the double bond is more realistic. This is illustrated below for 4-t-butyl-1-cyanocyclohexene and 4,4-dimethyl-1-cyanocyclohexene.





As discussed in section 1.2, the bromine atom approaches the double bond perpendicularly from above as this results in the more stable chair form intermediate radical. Approach in a similar manner from below would result in the twist-boat form. At the low temperature of the reaction, the energy difference between the two possible transition states may be large enough to dictate exclusively the pathway involving the chair form. In the t-butyl compound this would result in the exclusive formation of the axially substituted isomer.

No addition of hydrogen bromide to 4,4-dimethyl-1-cyanocyclohexene could be obtained and the lack of addition in this case suggests that the steric inhibition of the axial methyl group prevents bromine atom approach from the top. Thus, synthesis of 4,4-dimethyl-2-bromocyclohexylformyl peroxide by the route described in section 3.5 for the t-butyl analogue was not possible.

The addition of hydrogen bromide to 4-t-butylcyclohexene resulted in a mixture of 3- and 4-t-butyl-1-bromocyclohexane. N.m.r. spectroscopy indicated that the bromine was exclusively axial.

2.4. The synthesis and decomposition of di-trans-4-t-butylcyclohexylformyl and di-trans-4-t-butyl-cis-2-bromocyclohexylformyl peroxides

The unsuccessful synthesis of the aldehyde and azo analogues of the 4-t-butyl-2-bromocyclohexane (XXXIX) diverted attention to the synthesis of di-trans-4-t-butyl-cis-2-bromocyclohexylformyl peroxide.

Fig (III)

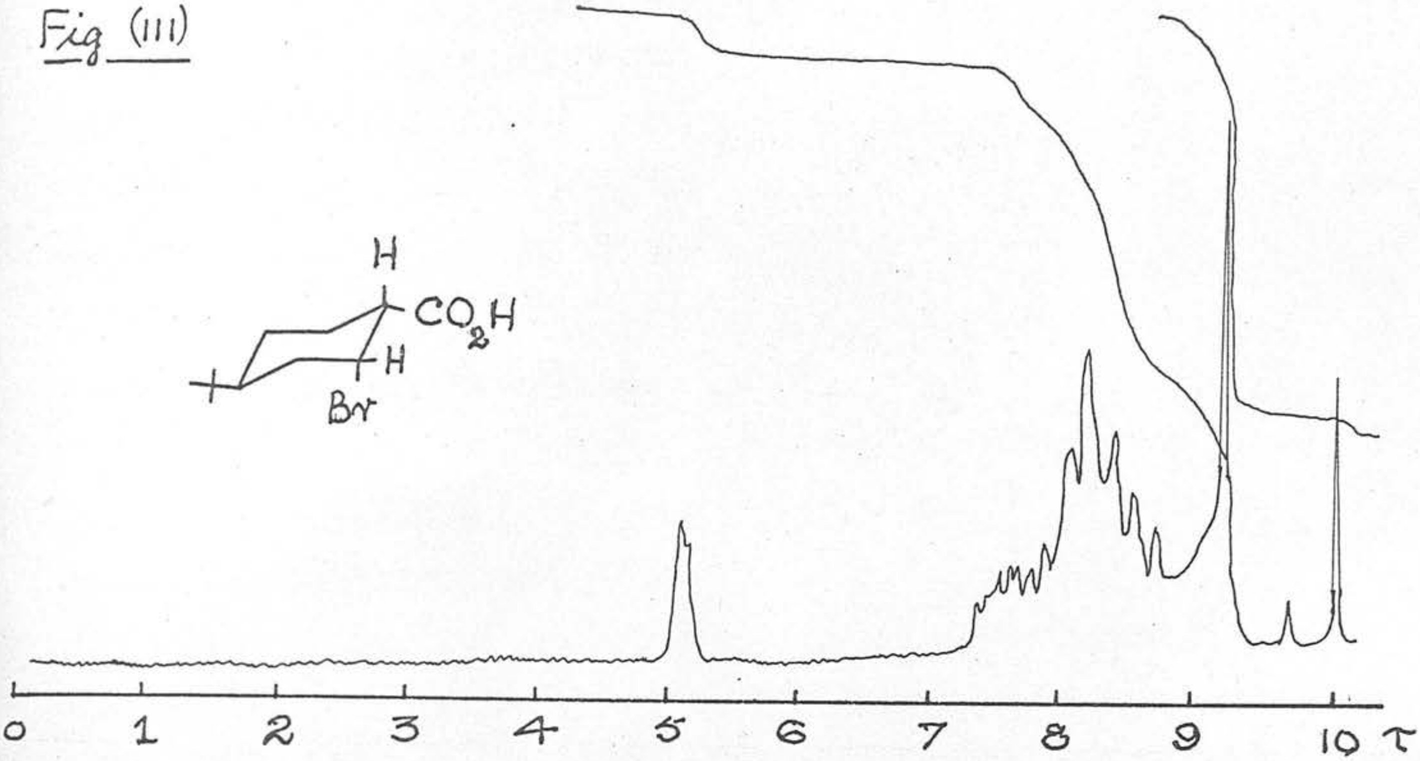
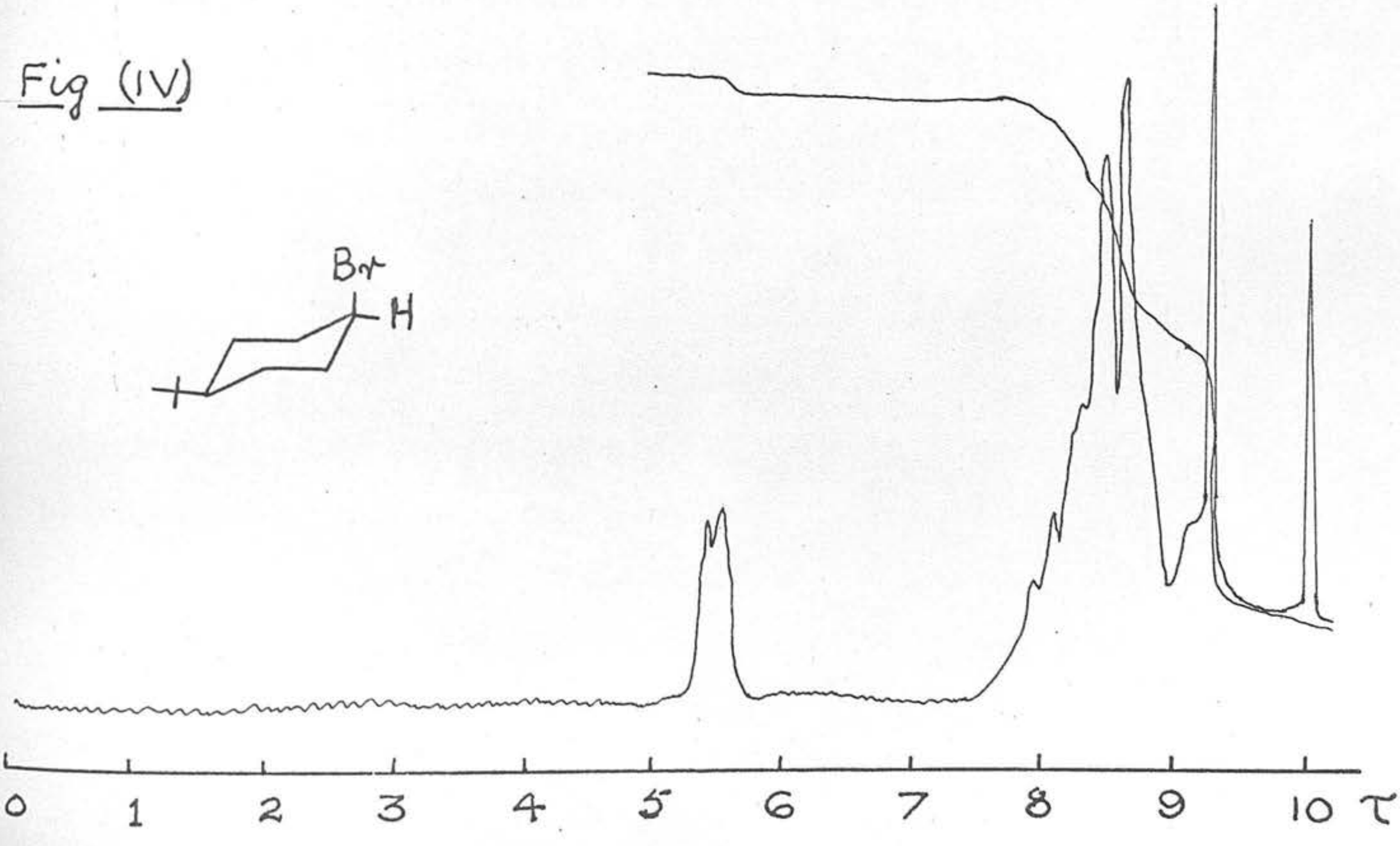
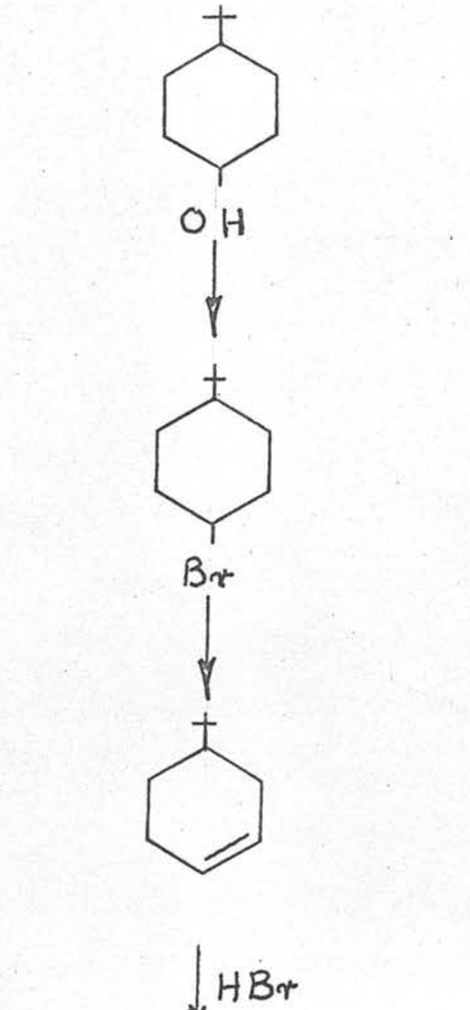


Fig (IV)




OH
Br
HBr
Br
+
Br
OH
OH

Treatment of trans-4-t-butyl-cis-2-bromocyclohexane-1-carboxamide with saturated aqueous potassium nitrite in sulphuric acid gave a low yield (18%) of trans-4-t-butyl-cis-2-bromocyclohexane-1-carboxylic acid (XLXI). The structure was verified by n.m.r. analysis (see fig. III). The low yield persisted throughout a series of experiments with varying quantities of sulphuric acid and potassium nitrite. The preparation was carried out below 10°; increase in temperature caused dehydrobromination of the product yielding a mixture of (XLXI) and the unsaturated analogue 4-t-butylcyclohexene-1-carboxylic acid. In view of this, and the previously observed dehydrobrominations during hydrolyses of the nitrile and amide, (discussed in section 2.3), alternative methods of hydrolysis were not possible.

4-t-butyl-2-bromocyclohexylformyl peroxide (XLXV) was prepared in 50% yield from the acid (XLXI) with hydrogen peroxide and dicyclohexylcarbodiimide.

The possible products of the decomposition of the peroxide, namely, the 3- and 4-t-butyl-1-bromocyclohexanes, were prepared from the corresponding alcohols with hydrobromic acid in sulphuric acid.

These isomeric bromocyclohexanes could not be separated by gas-liquid chromatography, however, treatment with silver tetrafluoroborate in dimethyl sulphoxide and triethylamine, converted the bromides to the corresponding ketones. Separation and identification of these was achieved by g.l.c. analysis.

The generation of radicals of type (XLXVI), (section 2.1.)

requires the loss of carbon dioxide from the acyloxy radical produced by thermal decomposition of 4-t-butyl-2-bromocyclohexylformyl peroxide. This necessitated finding a suitable solvent in which this reaction could take place and which would give the maximum yield of the required radical.

In selecting the solvent, a balance had to be reached between this process and that involving hydrogen abstraction by the acyloxy radical to produce the acid. That is, the solvent had to possess a hydrogen of suitable reactivity to allow loss of carbon dioxide before abstraction occurred. Competing with the hydrogen abstraction step would be the dimerisation of the radical (XLXVI) produced.

As 4-t-butyl-2-bromocyclohexylformyl peroxide was in short supply, preliminary experiments were performed using the parent compound, 4-t-butylcyclohexylformyl peroxide. The reaction conditions giving the optimum yield of t-butylcyclohexane were found for this on the assumption that similar conditions would hold for the bromo analogue.

The decompositions in chloroform, carbon tetrachloride and toluene at 80° and benzene at 55° resulted in a 30% yield of 4-t-butylcyclohexane-1-carboxylic acid and very small (<5%) yields of t-butylcyclohexane. In cyclohexane at 80° the acid production was again 30% but the hydrocarbon yield was greater (25%). The introduction of methyl thioglycollate resulted in a similar acid production and varying amounts of hydrocarbon depending on the concentration of thiol in the mixture. In pure methyl thioglycollate, no t-butylcyclohexane was formed and the acid production was increased to 60%. The optimum conditions, giving 50% t-butylcyclohexane and 30% acid, were in cyclohexane containing 10% methyl thioglycollate at 80°.

A similar series of experiments was carried out using 4-t-butyl-2-bromocyclohexylformyl peroxide. In view of the results obtained with the parent peroxide, cyclohexane containing varying proportions of methyl thioglycollate at 80° was the solvent system initially investigated. However, the low acid yields (15-20%) and the observation of very low yields (<2%) of 3- or 4-t-butyl-1-bromocyclohexane suggested that this peroxide was not behaving in an analogous manner to the parent compound under similar conditions.

The decomposition in cyclohexane at 65° gave an increased yield (38%) of acid, indicating that the higher temperature is required for carbon dioxide loss. This reaction also yielded 4-t-butylcyclohexene, a product observed (13%) as its 1:1 adduct with methyl thioglycollate in the decomposition of the peroxide in a 1:1 mixture of cyclohexane and methyl thioglycollate at 80°.

In the decomposition in cumene at 80° the acid production was very much lower (6%) but any 4-t-butylcyclohexene present could not be separated from the solvent by g.l.c. analysis. In none of the above experiments was any 3- or 4-t-butyl-1-bromocyclohexane observed.

The results indicate that though some elimination of bromine from (XLXVI) is taking place this does not seem to be followed by re-addition to the double bond so formed. The fairly low acid production and absence of bromo compounds from the reaction mixtures studied (by g.l.c. analysis), suggests that under the conditions employed the bulk of the radicals (XLXVI) is dimerising.

A preparative scale reaction to isolate these products and further adjustment of the experimental conditions to give the maximum yield of the radicals (XLXVI) without concomitant dimerisation are necessary to complete the investigation.

SECTION 3

Experimental

3.1. Introduction

Liquids and solutions were dried over magnesium sulphate before distillation or solvent removal.

Infra-red spectra were recorded on a Unicam SP200 instrument. Samples were examined at room-temperature (17-23°) as nujol mulls or as solutions in chloroform, or carbon disulphide.

Nuclear magnetic resonance spectra were recorded on a Perkin-Elmer R10 (60 m/c) instrument. Samples were examined at 33° as pure liquids or as solutions (5-20%) in deuterochloroform or carbon tetrachloride. Chemical shifts (τ) are expressed relative to that for tetramethylsilane which is taken to be 10 p.p.m.

Abbreviations used in the quoting of spectroscopic data are;

i.r.: (s), strong absorption; (m), medium; (w), weak.

n.m.r.: (s), singlet; (d), doublet; (m), multiplet.

The literature values for physical constants marked with an asterisk (i.e. Lit.*,) were taken from "The Dictionary of Organic Compounds"; Eyre and Spottiswood; London, 1965.

3.2. The synthesis of 4-t-butyl-2-bromo-1-cyanocyclohexane

4-t-butylcyclohexanone was prepared by the method of Warnhoff[89] et al. 4-t-butylcyclohexanol (624g. 4 moles) was dissolved by heating in benzene (2·3 l.) and the solution placed in a 10 l. flange-neck flask, fitted with a dropping funnel, stirrer and thermometer. To a solution of sodium dichromate (476g. 1·82 moles) in water (2 l.) was added sulphuric acid (648 ml. sp.gr. 1·84) and glacial acetic acid (200 ml.). The oxidising mixture was added to the alcohol over a period of 4 hours, the temperature being maintained at 8-10° throughout by immersion of the reaction vessel in an ice bath. The mixture was stirred for a further 3 hrs., after the addition was complete.

The aqueous layer was separated and extracted with benzene (2 x 500 ml.). The extracts were combined with the benzene layer and the whole washed in turn with water (500 ml.), sodium bicarbonate solution (400 ml.), sodium chloride solution (400 ml.) and dried. Removal of benzene on the rotary evaporator yielded the crude solid product which was melted and distilled, under nitrogen, through a 'Dixon ring' column. Yield 78%. b.p. 106°/17 m.m. (Lit.[90], 106-108°/18 m.m.)

4-t-butyl-1-cyanocyclohexene was prepared by a method based upon that of Ruzicka and Brugger.[91] The experiment was carried out in the fume cupboard. A solution of sodium cyanide (300g. 6·1 moles) in water (300 ml.) was added to 4-t-butylcyclohexanone (100g. 0·65 moles) in ether (400 ml.). The mixture was cooled in an ice bath and hydrochloric acid (300 ml. sp. gr. 1·19) added over a period of 3 hours with stirring.

The ether layer was separated and washed with water. The combined ether extracts were dried and the solvent removed on a water bath. The residue was taken up in benzene (200 ml.), dried and thionyl chloride (120 ml.) added. Dehydration was achieved by refluxing for 60 hours. (This period was arrived at after various unsuccessful experiments had yielded a large proportion (*ca.*, 50%) of the original ketone in the final product).

The mixture was cooled and poured into ice-water. The benzene layer was separated, washed with aqueous sodium hydroxide until the washings were alkaline and then water until neutral to universal indicator paper, dried and the benzene removed on the rotovapor.

The dark coloured residue (80g.), which solidified on standing, was taken up in petroleum (60/80°), decolourising charcoal (2g.) added, and boiled for 15 mins. After cooling, filtration yielded colourless crystals which were washed with petroleum and dried. Successive crystallisations yielded a total of 70g. (67%) 4-t-butyl-1-cyanocyclohexene. m.p. 45-46°. (Found: C, 80·92; H, 10·25; N, 9·06. $C_{11}H_{17}N$ requires C, 80·92; H, 10·50; N, 8·58%). i.r. ($CHCl_3$); 2250 (s) (C≡N); 1645 (s) (C=C); 1390 (s) $cm.^{-1}$ (t-butyl). n.m.r. (CCl_4); τ 3·45 (m) (olefinic H); 7·80 (m) (methylene protons); 9·10 (s) (t-butyl).

4-t-butyl-2-bromo-1-cyano-cyclohexane was prepared by a method based upon that of Skell and Readio.[62]

4-t-butyl-1-cyanocyclohexene (10g. 0·06 mole) was dissolved in dry n-hexane (130 ml.) in a conical flask fitted with a dry-ice condenser and immersed in a dry-ice/acetone bath at -78°. The flask had been previously flushed with nitrogen. The mixture was stirred and excess hydrogen bromide gas condensed into the flask. After irradiating with ultra-violet light for 2 hours, the mixture was allowed to reach room temperature and the excess hydrogen bromide removed by the passage of a stream of dry nitrogen.

A white solid which had separated was removed by filtration and dried (1·0g.). The hexane solution was washed with water, aqueous sodium bicarbonate and dried. Evaporation of the hexane yielded 12·5g., of residue which solidified on cooling. Recrystallisation from n-hexane yielded trans-4-t-butyl-cis-2-bromo-1-cyanocyclohexane. 7·6g. 51%. m.p. 65-66°. (Found: C, 54·19; H, 7·77. $C_{11}H_{18}NBr$ requires C, 54·14; H, 7·36%). i.r. (CS_2) 2250 (s) (C≡N); 1390 (s) (t-butyl); 660 (s) cm.$^{-1}$ (axial bromine). n.m.r. (CCl_4) τ 5·25 (d) (Proton in equatorial position on C_2[62]); 7·2 (m), 8·0 (m) (aliphatic protons); 9·12 (s) (t-butyl). (See section 2.3 and fig. (i))

The experiment was repeated using 20g. (0·12 mole) of the nitrile in 100 ml. n-hexane. The mixture was stirred overnight to remove excess hydrogen bromide, this time in the absence of nitrogen, and worked up as before. The yield of 4-t-butyl-2-bromo-1-cyanocyclohexane was 6·5g. (22%). The white solid material insoluble in n-hexane (10·7g. 33%) was identified as trans-4-t-butyl-cis-2-bromo-cyclohexane-1-carboxamide. m.p. 149°. (Found: C, 50·18; H, 7·28. $C_{11}H_{20}ONBr$ requires C, 50·42; H, 7·63%). i.r. (nujol); 3380 (s), 3480 (s) (NH); 1660 (s) (C=O); 1390 (s) cm.$^{-1}$ (t-butyl). n.m.r. ($CDCl_3$) τ 3·90 (s) (NH_2); 4·95 (s) (Proton in equatorial position on C_2); 8·0 (m) (aliphatic H); 9·10 (s) (t-butyl). (See fig. (ii).

In the second experiment described above, the major product was the amide. Modification of the procedure enabled the experiment to be used as the amide synthesis.

The unsaturated nitrile (15g. 0·09 mole), was dissolved in n-hexane (150 ml.) at -78° and liquid hydrogen bromide added as described previously. After irradiating with ultra-violet light for 4 hours, water (5 ml.) was added and the mixture stirred at room-temperature overnight. Two layers separated. The upper (hexane) layer was washed with water (30 ml.), aqueous sodium bicarbonate (2 x 30 ml.), water again, dried and evaporated to give a mixture (4g.) of starting material and amide.

The lower layer was dissolved in chloroform, washed with water, sodium bicarbonate solution, dried and evaporated to give the amide (15g. 63%).

The above conditions were found to be the optimum for amide production. A smaller volume of water resulted in a decreased yield whilst a larger volume (e.g. 10 ml.) resulted in hydrolysis to the unsaturated 4-t-butylcyclohexene-1-carboxylic acid by the resulting aqueous acid mixture.

In order to study the product composition and the possible mechanism, a series of reactions was carried out on a small scale in hexane solution. The reactions were performed both at room-temperature and at -78°, both with and without ultra-violet light and in some cases in the presence of hydroquinone to inhibit the free radical mechanism.

The reactions at -78° were carried out as described above, those at room-temperature were performed by bubbling hydrogen bromide gas through a solution of the nitrile in a quartz test tube.

Immediately the reaction period was over, a known weight of 1,4-dichloronaphthalene was added as an internal standard for the g.l.c. estimation of 4-t-butyl-1-cyanocyclohexene and the adduct, 4-t-butyl-2-bromo-1-cyanocyclohexane. The excess solvent and hydrogen bromide were removed by bubbling nitrogen through the solution and the residue dissolved in chloroform prior to g.l.c. analysis.

The results are summarised in the table below.

Number	Temp.	U.V.	Time (hr)	A	A'	B	%B	Accountancy %	I
1	20	No	0·75	1·881	0·077	0·848	45	50	0·000
2	20	No	0·75	1·269	0·344	0·336	28	54	1·275
3	-78	No	2·25	1·838	0·287	0·586	32	50	0·184
4	-78	Yes	2·25	1·900	0·218	1·384	73	84	0·000

A and A': m.moles of 4-t-butyl-1-cyanocyclohexene present at start and finish respectively.

B: m.moles of adduct (4-t-butyl-2-bromo-1-cyanocyclohexane).

I: m.moles of hydroquinone inhibitor.

The accountancy by g.l.c. analysis is poor in the cases of the reactions performed in the absence of ultra-violet, as is the yield of adduct. The accountancy in the reaction performed under free radical conditions (No.4) in the presence of ultra-violet is consistent with that already observed in the preparative scale reaction previously described.

3.3. Hydrolysis of the nitrile with aqueous acid.

(i) 4-t-butyl-1-cyanocyclohexene (5g. 0·03 moles) was hydrolysed to 4-t-butylcyclohexene-1-carboxylic acid by refluxing in 50% (v/v) sulphuric acid (200 ml.) for 3 hours. The product was recrystallised from n-hexane. Yield, 3·4g. (60%). m.p. 192-193°. (Found: C, 72·63; H, 9·77. $C_{11}H_{18}O_2$ requires C, 72·54; H, 9·87%). i.r. (CS_2) 2600 (w) (bonded OH); 1685 (s) (C=O in α, β-unsaturated acid); 1650 (m) (C=C); 1390 (m) cm.$^{-1}$ (t-butyl). n.m.r. ($CDCl_3$); τ 2·78 (s) (olefinic H); 7·80 (m) (aliphatic protons); 9·10 (s) (t-butyl); acidic H 200 c.p.s. downfield.

(ii) The acid was also obtained by refluxing 4-t-butyl-2-bromo-cyclohexane-1-carboxamide (4g. 0·02 mole) for 3 hr., with 50% (v/v) sulphuric acid (200 ml.). The yield was 50%.

(iii) The hydrolysis of 4-t-butyl-2-bromo-1-cyanocyclohexane (2·0g. 0·008 mole) was achieved by refluxing with 50% (v/v) sulphuric acid (200 ml.) for 3 hr. Again the product was the unsaturated acid (50% yield).

The acid was used for the preparation of the corresponding acid chloride and amide.

4-t-butylcyclohexene-1-carbonyl chloride (33g. 81%) was prepared by refluxing 4-t-butylcyclohexene-1-carboxylic acid (37g. 0·2 mole) with thionyl chloride (200 ml.) for 2 hours. The excess thionyl chloride was removed as an azeotrope with benzene under reduced pressure. The acid chloride was distilled using a vigreaux column. b.p. 162°/35 m.m. i.r. (Liquid film);

1740 (s) (C=O); 1640 (s) (C=C); 1390 (s) (t-butyl); 705 (s) and 660 (s) $cm.^{-1}$ (C-Cl). n.m.r. (CCl_4); τ 2·60 (m) (olefinic H); 7·70 (m) (aliphatic H); 9·10 (s) (t-butyl).

4-t-butylcyclohexene-1-carboxamide (7·8g. 80%) was prepared from the acid chloride (11·5g. 0·06 mole) in benzene (50 ml.) and excess ammonium hydroxide (sp. gr. 0·910). The product was recrystallised from ethanol. m.p. 183-184°. (Found: C, 72·49; H, 10·22. $C_{11}H_{19}NO$ requires C, 72·88; H, 10·57%). i.r. ($CHCl_3$); 3420 (s) (NH_2); 1680 (s) (α,β-unsaturated C=O); 1640 (s) (C=C); 1390 (m) $cm.^{-1}$ (t-butyl). n.m.r. ($CDCl_3$); τ 3·30 (m) (olefinic H); 4·20 (s) (NH_2); 7·60-8·80 (m) (aliphatic H); 9·12 (s) (t-butyl).

3.4. The reduction of nitrile to aldehyde

The reduction of the nitrile function was attempted using three reagents.

i) Lithium triethoxyaluminohydride

The reagent was prepared according to the method of Brown[92] et al. by adding dry ethanol (12·8g. 16 ml.) dropwise to a suspension of lithium aluminium hydride (3·85g. 0·1 mole) in ether (100 ml.) at 0°.

4-t-butyl-1-cyanocyclohexene (5g. 0·03 mole) was added to the mixture at 0°. The semi-solid mass was stirred for 1 hour. The excess lithium aluminium hydride and the complex with ethanol were destroyed by the addition of methanol. The greyish suspension was filtered, the filtrate taken up in ether, dried and the ether evaporated. The resulting residue was examined by i.r. analysis and found to be starting material (4·8 g.)

ii) Lithium aluminium hydride

The reduction was carried out by the method of Smith and Rogier.[93] A solution of lithium aluminium hydride (0·4g. 0·015 mole) in ether (200 ml.) was prepared using a Soxhlet extractor and refluxing for 75 hrs. under nitrogen. 4-t-butyl-1-cyanocyclohexene (5·6g. 0·04 mole) was dissolved in ether (200 ml.) and the lithium aluminium hydride solution added dropwise with stirring. The mixture was stirred for a further 4 hrs. under nitrogen, hydroquinone (0·1g.) added and the solution acidified with 10% sulphuric acid. Extraction with ether gave a quantitative recovery of starting material.

The experiment was repeated by adding a suspension of lithium aluminium hydride (0·2g. 0·005 mole) in ether (40 ml.) to 4-t-butyl-1-cyanocyclohexene (2g. 0·012 mole) in ether (60 ml.). The mixture was stirred at room temperature for 1 hr., then refluxed for 1½ hrs. The excess lithium aluminium hydride was destroyed by the cautious addition of water and the mixture acidified with 10% aqueous sulphuric acid. The product was extracted with ether. Again, a quantitative recovery of starting material was obtained.

Similarly, when 4-t-butyl-2-bromo-1-cyanocyclohexane (2g. 0·008 mole) in ether (100 ml.) was treated with a suspension of lithium aluminium hydride (0·08g. 0·002 mole) under the same conditions, the starting material was returned unchanged.

In none of the above reductions was any amine detected.

iii) Reduction via the acyl aziridine

1-(4-t-butylcyclohexene carbonyl) aziridine was prepared by the method of Brown and Tsukamoto.[94] 4-t-butylcyclohexene-1-carbonyl chloride (33g. 0·17 moles) was dissolved in ether (10 ml.) and added dropwise,over the period of 1 hour, with stirring to an ice-cooled solution of ethyleneimine (7·1g. 8·5 ml. 0·17 mole) and triethylamine (16·5g. 22·6 ml. 0·17 mole) in ether (100 ml.). The mixture was stirred for a further 30 minutes and the precipitated triethylamine hydrochloride removed by filtration and washed with ether.

The combined ethereal phases were cooled to 0° in an ice-salt bath and a suspension of lithium aluminium hydride (1·9g. 0·05 mole) in ether (100 ml.) added over a period of 30 min. The mixture was stirred for a further 60 min., and 5N sulphuric acid (100 ml.) added dropwise.

The ether layer was separated and the aqueous phase extracted with ether. The ether extracts were washed with water, aqueous sodium bicarbonate, water again, dried and the ether evaporated. G.l.c. analysis of the residue (21·5g.) showed two peaks in the ratio 1:9, the major component being the required aldehyde. The mixture was purified by column chromatography using silica gel (350g.) and eluting with ether.

The first fractions (total volume 300 ml.) contained only 4-t-butylcyclohexene-1-carboxaldehyde (18·5g. 68%). m.p. 170°.

(Found: C, 79·46; H, 10·92. $C_{11}H_{18}O$ requires C, 79·62; H, 10·53%). i.r. (CS_2); 1690 (s) (C=O, α,β-unsaturated aldehyde); 1645 (s) (C=C); 1390 (s) $cm.^{-1}$ (t-butyl). n.m.r. ($CDCl_3$); τ 3.15 (m) (olefinic H); 8·00 (m) (aliphatic H); 9·10 (s) (t-butyl).

The second 300 ml. eluate contained a mixture of the aldehyde and 4-t-butyl-1-hydroxymethylcyclohexene in the ratio 1:6. The aldehyde was removed from the mixture as the bisulphite addition compound, leaving the alcohol, 4·0g. (14%). (Found: C, 78·36; H, 11·33. $C_{11}H_{20}O$ requires C, 78·51; H, 11·98%). i.r. (liquid film); 3350 (s) (OH, primary alcohol); 1680 (w) (C=C); 1390 (s) $cm.^{-1}$ (t-butyl). n.m.r. ($CDCl_3$) τ 4·29 (s) (olefinic H); 6·00 (s) (CH_2 adjacent to OH); 7·65 (s) (OH); 8·00-9·00 (m) (aliphatic CH_2); 9·10 (s) (t-butyl).

3.5. The peroxide syntheses

4-t-butylcyclohexylformyl peroxide was prepared by the method of Greene and Kazan.[35]

A solution of 4-t-butylcyclohexane-1-carboxylic acid (2g. 0·011 moles) in redistilled methylene chloride (25 ml.) was added dropwise to an ice cooled mixture of dicyclohexylcarbodiimide (0·24g. 0·011 moles) and hydrogen peroxide (98%. 1·3 ml. 1·9g. 0·05 mole) in ether (25 ml.). The mixture was stirred for 1 hr., the temperature being maintained below 5°. The precipitated dicyclohexylurea was filtered off (2·0g. 90%) and washed with cold methylene chloride (3 x 20 ml.) by slurrying. Ether (100 ml.) was added, the solution washed with cold saturated aqueous ammonium sulphate (2 x 25 ml.); cold 10% aqueous sodium carbonate (3 x 25 ml.) and cold saturated aqueous sodium chloride (2 x 25 ml.). After drying, the ether was removed under reduced pressure at room temperature, depositing the white solid peroxide which was recrystallised by taking up in the minimum quantity of cold chloroform and adding double this quantity of methanol. Purity 98%. m.p. 68-70° (Lit.[95] 75°) i.r. ($CHCl_3$) 1760 (s) (Peroxidic C=O); 1390 (s) $cm.^{-1}$ (t-butyl).

4-t-butyl-2-bromocyclohexylformyl peroxide was prepared in an analogous manner. The parent acid was prepared from the amide by the method of Carter and Slater.[96] 4-t-butyl-2-bromocyclohexane-1-carboxamide (8·0g. 0·03 mole) was dissolved in sulphuric acid (30 ml. sp. gr. 1·84) and cooled in an ice salt bath. A saturated solution of sodium nitrite was added dropwise with stirring, maintaining the temperature below 20°, until the reaction mixture became semi-solid. The mixture was poured into ice water (200 ml.) and the organic material extracted with ether (3 x 50 ml.). The ether layer was washed with water, dried and evaporated, yielding 6·0g. (75%) unchanged amide.

The alkaline aqueous layer was acidified with hydrochloric acid (sp. gr. 1·19) and the liberated acid extracted with ether. The ether was washed, dried and evaporated, yielding 4-t-butyl-2-bromocyclohexane-1-carboxylic acid. 1·4g. (18%). m.p. 188-189° (From ethanol-water). (Found: C, 50·59; H, 7·19; Br, 29·35.

$C_{11}H_{19}O_2Br$ requires C, 50·30; H, 7·23; Br, 30·18%). i.r. (nujol); 2700 (m) (bonded OH); 1710 (s) (C=O); 1390 (m) (t-butyl); 675 (w) $cm.^{-1}$ (C-Br). n.m.r. ($CDCl_3$); τ 5·00 (d) (Equat. H); 8·10 (m) (aliphatic CH_2); 9·18 (s) (t-butyl); acidic proton 100 c.p.s. downfield. (See section 2.3 and fig. (iii).

The acid (0·5g. 0·002 mole) in redistilled methylene chloride (8 ml.) was added to an ice-cooled mixture of dicyclohexylcarbodiimide (0·42g. 0·002 mole) and hydrogen peroxide (98%. 0·73g. 0·5 ml. 0·013 mole) in ether (5 ml.). After stirring for 1 hr. at a temperature below 5°, the dicyclohexylurea (0·36g. 90%) was removed by filtration and washed by slurrying with methylene chloride (3 x 5 ml.). Ether (20 ml.) was added and washed as before. The ether was removed on the rotavapor yielding the peroxide (0·3g. 60%). Purity 99%. m.p. 93-95°. i.r. ($CHCl_3$) 1770(s) (C=O); 1390 (m) $cm.^{-1}$ (t-butyl).

3.6. The preparation of 4- and 3-t-butyl-1-bromocyclohexane

4-t-butyl-1-bromocyclohexane was prepared from 4-t-butylcyclohexanol (50g. 0·32 mole) by refluxing with a mixture of 48% hydrobromic acid and sulphuric acid (sp. gr. 1·98), total volume 600 ml., for 30 minutes. The lower acid layer was separated and discarded. The organic phase was taken up in ether (200 ml.), washed with aqueous sodium carbonate, (2 x 50 ml.), water (2 x 50 ml.), dried and the ether removed under reduced pressure.

The residue was distilled under nitrogen to give a yield of

35g. (50%). b.p. 105°/14 m.m. (Lit.[78], 80-81°/4 m.m.). i.r. (liquid film); 1390 (s) (t-butyl); 680 (s) and 650 (s) cm.$^{-1}$ (axial bromine). n.m.r. (CDCl$_3$) 5·35 (m) (Equatorial proton); 8·48 (m) (aliphatic CH$_2$); 9·15 (s) (t-butyl).

The spectroscopic evidence indicates the compound is *cis*-4-t-butyl-1-bromocyclohexane with the bromine in the axial position. (See section 2.3 and fig. (iv).

3-t-butyl-1-bromocyclohexane was prepared in an analogous manner.

3-t-butylcyclohexanone was prepared by the reduction of m-t-butylphenol according to the method of Benkeser[97] *et al.* The phenol (20g. 0·13 mole) was placed in a 500 ml. flask under nitrogen. The addition of lithium metal (10·6g. 1·5g. atom) and ethylamine (200 ml.) caused a vigorous reaction to take place turning the reaction mixture blue-black. After stirring for 7½ hr., ethanol (35 ml.) was added over a period of 2 hr., and the mixture allowed to stand overnight. The undecomposed lithium was removed with forceps and solid ammonium chloride (4g.) added. The resulting viscous paste was poured into water, shaken, and extracted with ether (3 x 100 ml.). The combined extracts were washed with water (2 x 100 ml.), dried and the ether removed under reduced pressure. The residue was distilled to give 3-t-butylcyclohexanone (12·0g. 60%). b.p. 115°/15 m.m. (Lit.[90], 92-95°/10 m.m.) i.r. (Liquid film); 1720 (s) (C=O); 1370 (s) cm.$^{-1}$ (t-butyl). n.m.r. (CDCl$_3$); τ 7·7-8·9 (m) (aliphatic protons); 9·10 (s) (t-butyl).

3-t-butylcyclohexanol was prepared by the reduction in methanol (20 ml.) of 3-t-butylcyclohexanone (5g. 0·03 mole) with sodium borohydride (0·37g. 0·01 mole) in water (10 ml.). The temperature was maintained between 20-30°. The product was extracted with ether, and distilled to give 2·5g. (50%) yield. b.p. 106-108°/12 m.m. (Lit.[90], 103°/10 m.m.). i.r. (Liquid film); 3500 (s) (OH); 1390 (s) cm.$^{-1}$ (t-butyl). n.m.r. ($CDCl_3$); τ 7·08 (s) (OH); 8·00-9·00 (m) (aliphatic CH_2); 9·10 (s) (t-butyl).

3-t-butyl-1-bromocyclohexane was prepared from the alcohol (2·0g. 0·01 mole) with 48% hydrobromic acid in a similar manner to that described above. wt. = 2·0g. (71%). b.p. 106°/14 m.m. (Lit.[78], 80-81°/4 m.m.). i.r. (Liquid film); 1390 (s) (t-butyl); 680 (m) cm.$^{-1}$ (axial bromine). n.m.r. (CCL_4); τ 5·31 (equatorial H); 7·59-8·60 (m) (aliphatic CH_2); 9·00 (s) (t-butyl).

Again the spectroscopic evidence suggests axial bromine.

4-t-butylcyclohexene was prepared by the dehydrobromination of 4-t-butyl-1-bromocyclohexane (10g. 0·45 moles) by refluxing for 20 hrs., with potassium hydroxide (40g. 0·71 mole) in ethylene glycol (250 ml.). The product (5·0g. 80%) had b.p. 168° (Lit.[98], 169°).

The addition of hydrogen bromide, with u.v. initiation,to 4-t-butylcyclohexene gave a mixture of the isomeric bromides; 4-t-butyl-1-bromocyclohexane and 3-t-butyl-1-bromocyclohexane. N.m.r. spectroscopy indicated exclusively axial bromine.

3.7. The synthesis of 4,4-dimethyl-1-cyanocyclohexene

This was prepared in a similar manner to the t-butyl analogue.

4,4-dimethylcyclohexanone cyanohydrin was kindly supplied by Dr. A.J. Bellamy.

A solution of the cyanohydrin (14g. 0·09 mole) in dry benzene (400 ml.) was refluxed for 3 days with thionyl chloride (120 ml.). On cooling, the mixture was poured into ice-water (500 ml.), the benzene layer separated, washed with aqueous sodium hydroxide, water, dried and distilled. The residual oil was distilled at reduced pressure yielding 4,4-dimethyl-1-cyanocyclohexene. 9·30g. (75%). b.p. 60°/1·0 m.m. (Found: C, 79·82; H, 9·81; N, 10·45. $C_9H_{13}N$ requires C, 79·95, H, 9·69, N, 10·36%). i.r. (liquid film); 2250 (s) (C≡N); 1640 (s) (C=C); 1390 (s) $cm.^{-1}$ (Dimethyl). n.m.r. ($CDCl_3$); τ 3·42 (m) (olefinic H); 7·70-8·00 (m) (aliphatic CH_2); 9·02 (s) (dimethyl group).

The attempted addition of hydrogen bromide to the unsaturated nitrile.

The reaction was carried out in a similar manner to that for the t-butyl analogue.

The nitrile (12·0g. 0·09 mole) was dissolved in n-hexane (150 ml.) at -78°. Liquid hydrogen bromide was condensed into the solution and the mixture irradiated with ultra-violet for 6 hours. After stirring at room temperature overnight, the organic material was extracted with ether, washed and dried. A quantitative recovery of starting material was obtained.

A similar result was obtained on carrying out the reaction at room temperature in chloroform solution in the absence of ultra-violet and in n-hexane with ultra-violet.

3.8. Hydrogen bromide additions

The addition of hydrogen bromide to 4-t-butylcyclohexene-1-carboxylic acid; 4-t-butylcyclohexene-1-carboxamide; 4-t-butylcyclohexene-1-carbonyl chloride and 4-t-butylcyclohexene-1-carboxaldehyde was investigated.

The reactions were attempted using procedures similar to those described for the addition to 4-t-butyl-1-cyanocyclohexene. In all the experiments summarised in the table below, the starting material was recovered unchanged.

g.	mole	Temp.	t(hr.)	Solvent (ml.)	u.v.
Acid.					
2·0	0·011	20	4	THF (30)	Yes
2·0	0·011	20	5	Ether (100)	Yes
1·0	0·005	-78	1	Hydrogen bromide	Yes
2·0	0·011	-78	2	Hydrogen bromide	Yes
2·0	0·011	-78	3	Hydrogen bromide	Yes
2·0	0·011	20	2	Chloroform (20)	No
Amide					
2·0	0·012	20	1·5	Chloroform (20)	No
2·0	0·012	-78	2·0	Hydrogen bromide	Yes
Acid Chloride					
2·0	0·010	20	0·2	n-Hexane (50)	Yes
2·0	0·010	20	2·0	n-Hexane (50)	Yes
2·0	0·010	-78	3·5	n-Hexane (75)	Yes
Aldehyde					
1·2	0·007	20	3·0	n-Hexane (30)	Yes
3·5	0·021	-78	1·5	n-Hexane (100)	Yes

3.9. Gas-liquid chromatography

Purification of materials

Biphenyl was recrystallised from light petroleum (40-60°) and had m.p. 71° (Lit.*, 71°).

Hexachloroethane was recrystallised from ethanol/ether and had m.p. 185-6° (Lit.*, 186-7°).

1,4-dichloronaphthalene was recrystallised from ethanol and had m.p. 67° (Lit.*, 67-8°).

Methyl thioglycollate had b.p. $51^{\circ}/20$ m.m. (Lit.[99], $49^{\circ}/16$ m.m.)

Bicyclohexyl, had b.p. $103^{\circ}/12$ m.m. (Lit.*, 233°).

t-butylcyclohexane had b.p. 168° (Lit.[100], 169-70°).

Relative retention times

The isomeric 3- and 4-t-butyl-1-bromocyclohexanes could not be separated on the columns and conditions used. Conversion to the corresponding ketones by the method of Lemal and Fry,[101] enabled these to be identified on 5% bentone/7% APL.

The bromo compound (0·270g. 1·20 m.moles) was added to silver fluoroborate (0·234g. 1·20 m.moles) in dimethylsulphoxide (10 ml.). The mixture was stirred for 1 hr., and excess triethylamine added. After stirring overnight the mixture was heated on a boiling water bath for 30 min., filtered into cold water and the ketone extracted with ether.

The g.l.c. analyses were performed on a Griffin D6 chromatograph. For a discussion of instrumentation see page 26.

The table below lists relative retention times, for 2 m.

columns, with a nitrogen inlet pressure of 15 lb./□ ".

The columns used were:

NPGS: 5% Neopentyl glycol succinate on 80/100 mesh acid washed and silanized chromosorb P.

PPE: 15% poly-m-phenyl ether (5 ring) on 80/100 mesh acid washed and silanized chromosorb P.

A/B: 5% Bentone/7% apiezon L grease on 80/100 mesh acid washed and silanized celite.

The Relative retention times are summarised in the table below.

Column	NPGS	NPGS	NPGS	PPE	PPE	PPE	A/B
Temperature	180	149	80	180	134	80	134
4-t-butyl-1-cyanocyclohexene	0·92						
4-t-butyl-2-bromo-1-cyanocyclohexene	5·49						
1,4-dichloronaphthalene	1·73						
4-t-butylcyclohexene-1-carboxaldehyde	0·73						
4-t-butyl-1-hydroxymethylcyclohexene	1·06						
4-t-butyl-1-bromocyclohexane	0·42			0·40	1·00		
3-t-butyl-1-bromocyclohexane	0·42			0·40	1·00		
biphenyl	1·00	1·00		1·00			
methyl thioglycollate	0·25		0·53	0·08			
methyl-4-t-butyl-2-bromocyclohexane-1-carboxylate	2·54						
methyl-4-t-butyl-1-cyclohexene carboxylate		0·38					
bicyclohexyl		0·21		0·29			
hexachloroethane		0·15					
t-butyl cyclohexane			0·14			2·4	
4-t-butylcyclohex-1-ene				0·09			
α-4-dimethylstyrene			1·00				
toluene						1·00	
bicumyl							
4-t-butylcyclohexanone							1·00
3-t-butylcyclohexanone							0·89
1:1 adduct of $HSCH_2CO_2Me$ + 4-t-butylcyclohexene				0·63			

3.10. Peroxide decompositions

The generation of radicals of type (XLXVI) (See page 106) requires the loss of carbon dioxide from the corresponding alkoxy radical produced by decomposition of the appropriate peroxide. This necessitated finding a suitable solvent in which this reaction could take place. As 4-t-butyl-2-bromocyclohexylformyl peroxide was in short supply, attention was turned to the parent compound, 4-t-butylcyclohexylformyl peroxide.

The conditions giving the optimum yield of the 4-t-butylcyclohexyl radical were found for this on the assumption that similar conditions would hold for the bromo analogue.

A series of experiments was carried out by dissolving the peroxide in the solvent under investigation, sealing in a tube under nitrogen, and decomposing in a thermostat oil bath for 12 hours.

The product composition was investigated by g.l.c. analysis after treatment with diazomethane, the addition of suitable internal standards and removal of solvents.

The reactions are summarised in the tables below.

Preliminary decompositions:

Temp.	Solvent (ml.)	Peroxide		Biphenyl	
		g.	m.mole	g.	m.mole
55	Chloroform (5)	0·0690	0·189	0·0223	0·145
55	Benzene (5)	0·0624	0·171	0·0220	0·145
80	Carbon Tet. (5)	0·0683	0·186	0·0215	0·140
80	Chloroform (5)	0·0686	0·186	0·0207	0·135
80	Toluene (5)	0·0671	0·184	0·0258	0·168

In the above, the acid production was similar (ca., 30%) in each case. Little (<5%) or no t-butylcyclohexane was detected. Some (<5%) bicyclohexyl from the dimerisation of solvent derived radicals was detected.

Decompositions in cyclohexane at 80°.

Solvent system (ml.)	Peroxide g.	Peroxide m.mole	Biphenyl g.	Biphenyl m.mole	α-4-dimethyl styrene g.	α-4-dimethyl styrene m.mole	t-butyl cyclohexane %
Cyclohexane(5)	0·0636	0·174	0·0230	0·149	0·0568	0·430	25
Cyclohexane(5) $HSCH_2CO_2Me$(0·1)	0·0597	0·163	0·0222	0·145	0·0635	0·480	26
Cyclohexane(5) $HSCH_2CO_2Me$(0·5)	0·0576	0·157	0·0244	0·159	0·0503	0·379	50
Cyclohexane(2·5) $HSCH_2CO_2H$(2·5)	0·0531	0·145	0·0223	0·145	0·0541	0·410	20
$HSCH_2CO_2Me$(1)	0·0139	0·038	0·0105	0·068	0·0341	0·258	0

The acid production (ca., 30%) remained constant throughout. The optimum yield of t-butylcyclohexane was obtained in cyclohexane containing 10% methyl thioglycollate. The reaction in neat thioglycollic acid resulted in a higher (60%) acid production and no t-butylcyclohexane.

A similar series of experiments was carried out with 4-t-butyl-2-bromocyclohexyl peroxide. The results are summarised in the table below.

Solvents (ml.)	Temp.	Peroxide		Acid		4-t-butyl cyclohexene	
		g.	m.moles	m.moles	%	m.moles	%
cyclohexane (1)	80	0·0500	0·0956	0·0306	15		
cyclohexane (2)	80	0·0436	0·0834	0·0320	19		
cyclohexane (5)	80	0·0436	0·0834	0·0280	17		
cyclohexane (5) methyl thioglycollate (0·5)	80	0·0387	0·0739	0·0264	18		
cumene (0·5)	80	0·0095	0·0180	0·0021	6		
cumene (1)	80	0·0123	0·0235	0·0012	5		
cyclohexane (1)	65	0·0089	0·0170	0·0068	38	0·0005	3
cyclohexane (0·5) methyl thioglycollate (0·5)	80	0·0049	0·0093	0·0038	21	0·0024*	13

* Estimated as the 1:1 adduct of methyl thioglycollate.

In the first two experiments there was only a trace (< 3 %) of any bromo compound and no 4-t-butylcyclohexene. In none of the others was any 3- or 4-t-butyl-1-bromocyclohexane found.

Bibliography

1. Szwarc and Roberts, J. Chem. Phys., 1950, *18*, 561.
2. Levy, Steinberg and Szwarc, J. Amer. Chem. Soc., 1954, *76*, 5978.
3. Swain, Stockmayer and Clarke, ibid., 1950, *72*, 5426.
4. Data supplied by Messrs. "Novadel", Ltd.
5. Raley, Rust and Vaughan, J. Amer. Chem. Soc., 1948, *70*, 88.
6. Raley, Rust and Vaughan, ibid., 1948, *70*, 1336.
7. Bell, Rust and Vaughan, ibid., 1950, *72*, 377.
8. Davies, 'Organic Peroxides', Butterworth, 1961.
9. Hey, J. Chem. Soc., 1934, 1966.
10. Wieland, *et al.*, Annalen., 1934, *513*, 93.
11. DeTar, Long, Rendleman, Bradley and Duncan, J. Amer. Chem. Soc., 1967, *89*, 4051.
12. Gill and Williams, J. Chem. Soc., (C) 1967, 1153.
13. Nozaki and Bartlett, J. Amer. Chem. Soc., 1946, *68*, 1686.
    1947, *69*, 2299.
14. Hammond and Soffer, ibid., 1950, *72*, 4711.
15. Bartlett and Cohen, ibid., 1943, *65*, 543.
16. Cass, ibid., 1946, *68*, 1976.
17. Foster and Williams, J. Chem. Soc., 1962, 2862.
18. Gill and Williams, ibid., 1965, 7127. 1966(B), 880.
19. Hey, Perkins and Williams, ibid., 1964, 3412.
20. Gill and Williams, ibid., 1965, 995.
21. Hey, Advances in Free Radical Chemistry, 1965, *2*, 73.
22. Walling and Savas, J. Amer. Chem. Soc., 1960, *82*, 1738.
23. Walling and Cekovic, ibid., 1967, *89*, 6681.
24. Cadogan, Hey and Hibbert, J. Chem. Soc., 1965, 3939.

1. Szwarc and Roberts, J. Chem. Phys., 1950, 18, 561.

2. Levy, Steinberg and Szwarc, J. Amer. Chem. Soc., 1954, 76, 5978.

3. Swain, Stockmayer and Clarke, ibid., 1950, 72, 5426.

4. Data supplied by Messrs. "Novadel", Ltd.

5. Raley, Rust and Vaughan, J. Amer. Chem. Soc., 1948, 70, 88.

6. Raley, Rust and Vaughan, ibid., 1948, 70, 1336.

7. Bell, Rust and Vaughan, ibid., 1950, 72, 377.

8. Davies, 'Organic Peroxides', Butterworth, 1961.

9. Hey, J. Chem. Soc., 1934, 1966.

10. Wieland, et al., Annalen., 1934, 513, 93.

11. DeTar, Long, Rendleman, Bradley and Duncan, J. Amer. Chem. Soc., 1967, 89, 4051.

12. Gill and Williams, J. Chem. Soc., (C) 1967, 1153.

13. Nozaki and Bartlett, J. Amer. Chem. Soc., 1946, 68, 1686.
1947, 69, 2299.

14. Hammond and Soffer, ibid., 1950, 72, 4711.

15. Bartlett and Cohen, ibid., 1943, 65, 543.

16. Cass, ibid., 1946, 68, 1976.

17. Foster and Williams, J. Chem. Soc., 1962, 2862.

18. Gill and Williams, ibid., 1965, 7127. 1966(B), 880.

19. Hey, Perkins and Williams, ibid., 1964, 3412.

20. Gill and Williams, ibid., 1965, 995.

21. Hey, Advances in Free Radical Chemistry, 1965, 2, 73.

22. Walling and Savas, J. Amer. Chem. Soc., 1960, 82, 1738.

23. Walling and Cekovic, ibid., 1967, 89, 6681.

24. Cadogan, Hey and Hibbert, J. Chem. Soc., 1965, 3939.

25. Schwartz and Leffler, J. Amer. Chem. Soc., 1968, 90, 1368.
26. Brydon and Cadogan, J. Chem. Soc., 1968(C), 819.
27. DeTar, J. Amer. Chem. Soc., 1967, 89, 4058.
28. Cooper, J. Chem. Soc., 1951, 3106.
29. Lamb, et al., J. Org. Chem., 1966, 31, 147.
30. Koenig and Martin, ibid., 1964, 29, 1520.
31. Greene, Adam and Cantrill, J. Amer. Chem. Soc., 1961, 83, 3461.
32. Abbott, Org. Synth., 1932, 12, 60.
33. Reimer, J. Amer. Chem. Soc., 1942, 64, 2510.
34. DeTar and Wells, ibid., 1960, 82, 5845.
35. Greene and Kazan, J. Org. Chem., 1963, 28, 2168.
36. Feiser and Leffler, J. Amer. Chem. Soc., 1948, 70, 3178.
37. Muramoto et al., Chem. Comm., 1968, 717.
38. Silbert and Swern, J. Amer. Chem. Soc., 1959, 81, 2364.
39. Koo, Fish, Walker and Blake, Org. Synth., 1951, 31, 35.
40. Roberts and Carboni, J. Amer. Chem. Soc., 1955, 77, 5556.
41. Benghiat and Becker, J. Org. Chem., 1958, 23, 885.
42. Campbell and Eglinton, Org. Synth., 1965, 45, 39.
43. Jacobs and Dankner, J. Org. Chem., 1957, 22, 1424.
44. Cadogan and Sadler, J. Chem. Soc.,(B), 1966, 1191.
45. Smith, Moffat and Khorana, J. Amer. Chem. Soc., 1958, 80, 6204.
46. Nelson and Bartlett, ibid., 1966, 88, 137.
47. McBay and Tucker, J. Org. Chem., 1954, 19, 869.
48. DeTar, et al. J. Amer. Chem.Soc., 1967, 89, 4051.
49. Skell, 'Organic Reaction Mechanisms'. Chem. Soc. Special Publication No.19, 1965, 131.

50. Hey and Waters, Chem. Rev., 1937, 21, 169.

51. Kharash, Englemann and Mayo, J. Org. Chem., 1937, 2, 288.

52. Mayo and Walling, Chem. Rev., 1940, 27, 351.

53. Tedder and Walton, Proc. Chem. Soc., 1964, 240.

54. Walling and Huyser, Organic Reactions, 1963, 13, 91.

55. Goering, Abell and Aycock, J. Amer. Chem. Soc., 1952, 74, 3588.

56. Roberts and Kimball, ibid., 1937, 59, 947.

57. Goering and Larsen, ibid., 1959, 81, 5937.

58. Goering and Sims, ibid., 1955, 77, 3465.

59. Pauling, 'The Nature of the Chemical Bond' 3rd ed., Cornell Univ. Press. 1960, 343.

60. LeBel, J. Amer. Chem. Soc., 1960, 82, 622.

61. Abell and Chaio, ibid., 1960, 82, 3610.

62. Readio and Skell, J. Org. Chem., 1966, 31, 753.

63. Skell and Woodworth, J. Amer. Chem. Soc., 1955, 77, 4638.

64. Cadogan and Duell, J. Chem. Soc. 1962, 4154.

65. Bohm and Abell, Chem. Rev., 1962, 62, 599.

66. Goering, Relgea and Larson, J. Amer. Chem. Soc. 1956, 78, 348.

67. Skell and Allen, ibid., 1960, 82, 1511.

68. Abell and Piette, ibid., 1962, 84, 916.

69. Symons, J. Phys. Chem., 1963, 67, 1566.

70. Skell and Readio, J. Org. Chem. 1966, 31, 759.

71. Bordwell, Landis and Whitney, ibid., 1965, 30, 3764.

72. Huyser and Jeffrey, Tetrahedron, 1965, 21, 3083.

73. LeBel and DeBoer, J. Amer. Chem. Soc., 1967, 89, 2784.

74. Noyes, Dickinson and Schomaker, ibid., 1945, 67, 1319.

75. Greenwood, ibid., 1957, 79, 5365.

76. Huyser, Benson and Sinnige, J. Org. Chem., 1967, 32, 622.

77. Thaler, J. Amer. Chem. Soc., 1963, 85, 2607.

78. Skell and Readio, ibid., 1964, 86, 3334.

79. Skell, Tuleen and Readio, ibid., 1963, 85, 2849.

80. Haag and Heiba, Tetradron Letters. 1965, 41, 3679.

81. Haag and Heiba, ibid., 1965, 41, 3683.

82. Skell, Allen and Gilmour, J. Amer. Chem. Soc., 1961, 83, 504.

83. Juneja and Hodnett, ibid., 1967, 89, 5685.

84. Allinger and Allinger, ibid., 1958, 50, 5476.

85. Walling, Kharasch and Mayo, ibid., 1939, 61, 2693.

86. Jackmann, "Applications of N.M.R. spectroscopy in Organic Chemistry", Pergamon Press Inc., N.Y., 1959, 115.

87. Lemieux, Kullnig, Bernstein and Schneider, J. Amer. Chem. Soc., 1958, 80, 2237.

88. Brace, ibid., 1962, 84, 3020.

89. Warnhoff, Martin and Johnson, Org. Synth., 1957, 37, 10.

90. Winstein and Holness, J. Amer. Chem. Soc., 1955, 71, 5562.

91. Ruzicka and Brugger, Helv. Chim. Acta., 1926, 9, 399.

92. Brown, Schaaf and Garg, Tetrahedron Letters, 1959, 3, 9.

93. Smith and Rogier, J. Amer. Chem. Soc., 1951, 73, 4047.

94. Brown and Tsukamoto, ibid., 1961, 83, 4549.

95. Lau and Hart, ibid., 1959, 81, 4897.

96. Carter and Slater, J. Chem. Soc., 1946, 130.

97. Benkeser, Arnold, Lambert and Thomas, J. Amer. Chem. Soc., 1955, 77, 6042.

98. Schmerling, ibid., 1947, 69, 1121.

99. Sokol and Ritter, ibid., 1948, 70, 3517.

100. Signaigo and Cramer, ibid., 1933, 55, 3326.

101. Lemal and Fry, Tetrahedron Letters, 1961, 775.