REACTIONS OF SOME VINYL RADICALS

A THESIS

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BY

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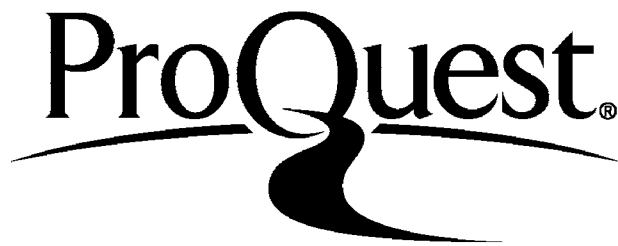BEDFORD COLLEGE

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INTRODUCTION

EXPERIMENTAL

INTRODUCTION

1) GENERAL DEVELOPMENTS IN THE STUDY OF HOMOLYTIC REACTIONS

There are two ways in which a covalent molecule may be disrupted during the course of a chemical reaction. In 1935, Waters[1] distinguished between the symmetrical cleavage of the covalent bond, which yields two neutral fragments, termed "FREE RADICALS", each possessing an odd unpaired electron,

$$A : B \longrightarrow A \cdot + B \cdot \quad\quad\text{---} \quad (1)$$
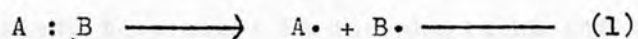
and its unsymmetrical cleavage, which gives rise to two ions of opposite charge.

$$A : B \longrightarrow A^{-} : + B^{+} \quad\quad\text{---} \quad (2)$$
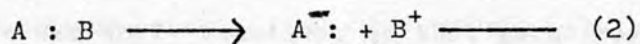
Ingold[2(a)], in 1938 called these modes of bond fission 'homolysis' and 'heterolysis' respectively. Since more energy is required to separate the charge particles of equation (2) than the neutral fragments of equation (1), it would appear that homolytic fission (as in equation (1)) would be more favoured than heterolysis (as in equation (2)). In the gas phase this seems to be true, although Ingold[2(b)] has caused some doubt to be thrown on the generality of this principle. For the majority of reactions in solution, however, particularly in solvents of high dielectric constant, heterolytic fission predominates, owing to the solvation of the ions produced, and this results in an energetic advantage being given to this mode of cleavage. Thus in solution, homolytic reactions are exceptional rather than general.

Organic free radicals fall into two classes:-
(i) those of long life, like the triarylmethyl radicals, which are greatly stabilized by resonance and (ii) those of short life,
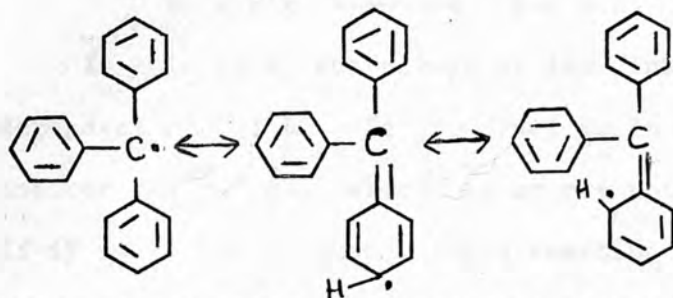
which do not enjoy such extensive stabilization.

From the fact that short-lived radicals can not be prepared in large quantities, they might be thought to be intrinsically unstable. This is not so, however and the reason why they can not be isolated lies not in that they readily break down, but in that they are extremely reactive, so that each fragment under-goes a chemical reaction of some sort in an attempt to satisfy its normal valency requirements before it has collided with many other molecules. A single radical, isolated completely from all contact with other molecules, would usually remain unchanged indefinitely. Thus the term 'short lived' which applied to a free radical, is meaningless unless the environ-mental conditions are also stated. However, the techniques used to detect radicals of the triarylmethyl type, such as colour reactions and magnetic measurements, fail completely when attempts are made to apply them to these short-lived radicals.

Free radicals have been found to react in three main ways.

(iii) in dimerization or combination of radicals

$$R\cdot + R\cdot \longrightarrow R - R \qquad (3)$$
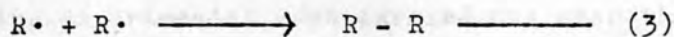
(iv), disproportionation which involves mutual hydrogenation and dehydrogenation;

$$2 \quad \overset{H}{\underset{|}{>}}C-\overset{\cdot}{C}< \quad \longrightarrow \quad >C=C< \; + \; \overset{H}{\underset{|}{>}}C-C\overset{/}{\underset{|}{-}}H \qquad (4)$$
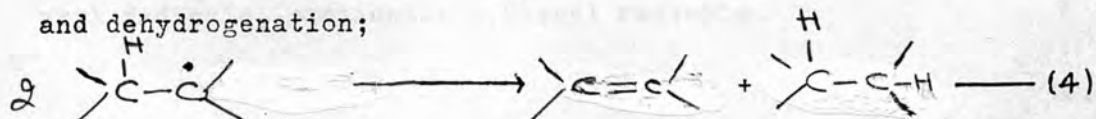
(v) by <u>radical transfer</u>, which may be represented thus;

$$R\cdot + R'x \longrightarrow R\cdot x + R'\cdot \quad\quad\quad (5)$$
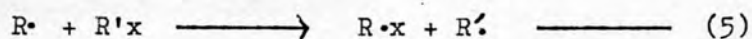
In this case, the nature of the final product is also dependent on the $R'\cdot$. It may react as in equation (5) to give another radical $R''\cdot$, which may or may not be the same as $R'\cdot$. If it is the same, then a chain reaction is set up and the process repeats itself until the chain is somehow interrupted. Should the radicals $R'\cdot$ and $R''\cdot$ be relatively unreactive, the transference represented by equation (5), results in the termination of the reaction.

Often the total reaction appears very complex owing to the simultaneous occurrence of reactions of all these types. In certain cases, however, some of these reactions are relatively more favoured than others, and specific compounds appears in the product in preponderance. With labile radicals in solution the radical-solvent interaction (equation (5)) is often the most important reaction, when it is clear that the product is determined by both the radical and the solvent. It has been found that alkyl and aryl radicals differ in their reactions with aromatic solvents. Similarly in a comparison of reactions of a given radical with aliphatic and aromatic solvents, only the latter are normally susceptible to homolytic substitution at carbon. Homolytic aromatic substitution reactions have been studied in considerable detail. Dermer and Edmison[3] have reviewed the experimental work carried out over the field, and Augood and Williams[4] have assessed the quantitative work on aryl radicals, particularly phenyl radicals.

2) HOMOLYTIC AROMATIC ARYLATION

Homolytic aromatic arylation has been extensively investigated[5].
Walling and Gibian[6] have shown that cyclohexyl radicals,
derived from cyclohexane via hydrogen abstraction by reaction with
photochemically excited ketones in the triplet states can
attack benzene to yield cyclohexylbenzene. Concurrently, in
the course of a study involving the reactions of hydrocarbons
with t-butoxy-radicals, it has been observed[7] that photolysis
of t-butyl peroxide in cyclohexane gave cyclohexylbenzene along
with coupled products when the reaction was conducted in benzene
solution. Photolysis of t-butyl peroxide in cyclohexane and
appropriate aromatic compounds resulted in partial conversion
of the peroxide to t-butoxy-radicals. The latter species mainly
abstracted hydrogen from cyclohexane, forming t-butyl alcohol
and cyclohexyl radicals, which subsequently coupled to form
bicyclohexyl, or attacked the aromatic solvent. Minor amounts
of acetone were also produced from the β scission of the
t-butoxy-radicals. The proposed mechanism[7] of the reaction is

$$(t\text{-}C_4H_9O)_2 \xrightarrow{h\nu} 2\,t\text{-}C_4H_9O\bullet$$

$$t\text{-}C_4H_9O\bullet + \bigcirc \longrightarrow t\text{-}C_4H_9OH + \bigcirc\bullet$$

$$2\,\bigcirc\bullet \longrightarrow \bigcirc\!\!-\!\!\bigcirc$$

$$\bigcirc\bullet + \bigcirc^{R} \xrightarrow{x} t\text{-}C_4H_9OH + \bigcirc\!\!-\!\!\bigcirc^{R}$$
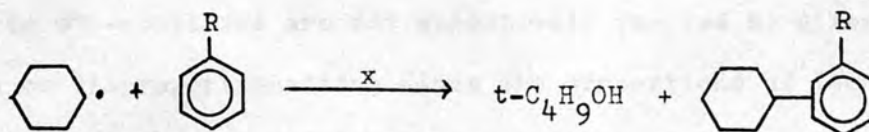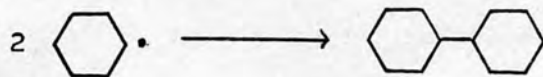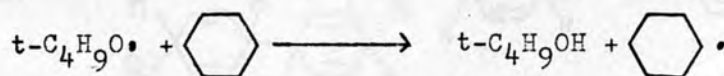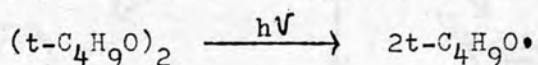
The yields of these products exceeds 50%, when an electron-attracting aromatic substitutent is present in the substrate, because cyclohexyl radicals are thought to have some nucleophilic character and nuclei containing electron-attracting groups are activated towards nucleophiles. The combined yields of bicyclohexyl and arylcyclohexanes, however never exceeded 60%, indicating that the t-butoxy-radicals and/or the σ-complex radical (cyclohexadienyl radical) can participate in processes other than dehydrogenation of the σ-complexes e.g. dimerization. The first step in σ-complex is the addition of the radical to the π-electron system of the nucleus, one of whose π-electrons becomes localized in the formation of a new bond. A resonance-stabilized cyclohexadienyl radical is produced.
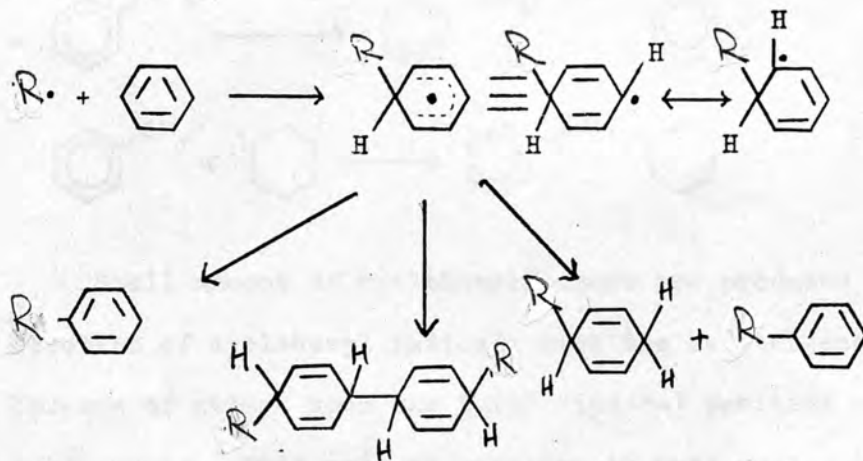
For arylation, however other workers[8] concluded that the isomeric σ-complexes are not selectively removed by dimerization or disproportionation, since the proportions of isomers actually observed are relatively insensitive to large changes in reaction conditions, which leads to large variations in the

extent to which the σ -complexes are removed by dimerisation or disproportionation. It has been found that t-butylbenzene gives the highest amount of bicyclohexyl in the cyclohexylation reaction, and excepting toluene, the lowest amount of arylcyclohexane, the low yield of cyclohexyltoluene may at first glance appear anomalous, but actually homolytic aromatic cyclohexylation is a minor process in this system in which the major products are phenylcyclohexylmethane and bibenzyl derived in whole or part from benzyl radicals. No benzyltoluenes resulting from homolytic benzylation of toluene could be detected in the reaction mixture.
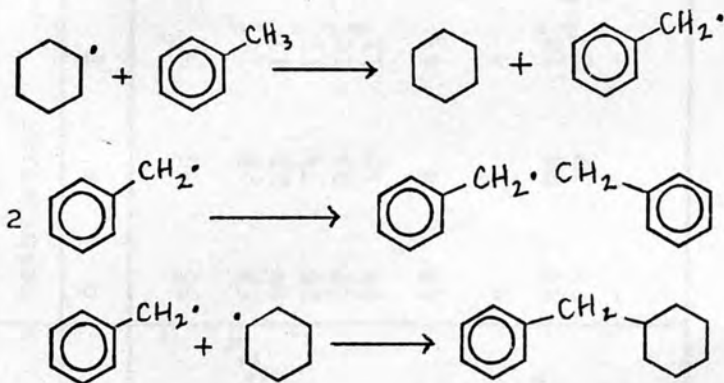
Small amount of cyclohexylbenzene are produced in the reaction of cyclohexyl radicals with the halobenzenes, because of attack upon the 1-(or "ipso"-) position of the halobenzene. This mode of reaction is very much enhanced by higher reaction temperatures, but does not seem to depend on whether the t-butyl peroxide decomposes thermally or photolytically. The following <u>Table A</u> shows the isomer distributions for free radical cyclohexylation together with the available data from the literature on phenylation and methylation.

Table A

Isomer percentages obtained in Homolytic Aromatic Substitutions.[9]

Aromatic	Cyclohexylation			Methylation			Phenylation		
	o	m	p	o	m	p	o	m	p
C_6H_5F	61	35	4[a]	58	37	5[c]	54	31	15[f,g]
C_6H_5Cl	54±2	34±2	12+2[b]	62 / 64	28 / 25	10[c] / 11[d]	50	32	18[f,h]
C_6H_5Br	58	32	10	55 / 67 / 74	34 / 23 / 15	11[c] / 10[d] / 11[d]	50	33	17[f,i]
$C_6H_5OCH_3$	67	28	5	48	9	43	69 / 79 / 60	18 / 10 / 10	13[j,k] / 11[f,l] / 30[f,m]
C_6H_5CN	52	4	44	–	–	–	29	41	30[f,n]
$C_6H_5CF_3$	6	52	42	59 / 56	29 / 27	12[d,e] / 17[d]	67	19	14[f,o]
$C_6H_5CH_3$	32	43	25[a]	–	–	–	24 / 10	49 / 63	27[f,p] / 27[q]
$C_6H_5C_4H_9\text{-}t$	0	72	28	–	–	–			

It may be seen that for those aromatic substitutents, which
are generally considered as ortho-para directors in electro-
philic substitution, the meta-/para- ratio generally increase
in the order: phenylation ⟨ methylation ⟨ cyclohexylation,
with those for phenylation near the statistical value of 2.0
and those for alkylation somewhat higher. Just the opposite
effect is observed in the case of the strongly electron
attracting cyano-group, for which cyclohexylation shows the
lowest meta-/para- ratio.

In cyclohexylation the proportion of para- substitution
is increased by a group which diminishes electron density at
this position, and is decreased by one which causes that region
of aromatic molecule to become relatively more electron rich.
Such directional effects are opposite to those normally
encountered in electrophilic aromatic substitution and
suggest increasing nucleophilicity of the radical attacking
species in the series

phenylation ⟨ methylation ⟨ cyclohexylation.

3) THE PRODUCTION OF FREE RADICALS IN THE REACTIONS OF
GRIGNARD REAGENTS WITH ORGANIC HALIDES IN THE PRESENCE
OF COBALTOUS CHLORIDE

Kharasch and Fields[10] described the results obtained
when aryl Grignard reagents were treated with organic halides
in the presence of a small quantity (3-5 mole percent) of the
halides of copper, manganese, nickel, chromium or cobalt.
They discovered that reaction of a Grignard reagent with an
organic halide in the presence of a catalytic quantity of
cobaltous chloride gave a coupling product derived from two
molecules of Grignard reagent. The coupling of Grignard
reagents by metallic halides in accordance with equation (6)

$$2RMgX + MX_2 \longrightarrow R-R + 2MgX_2 + M \quad\quad\quad (6)$$
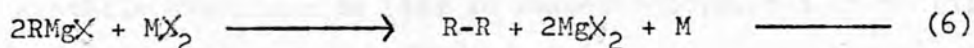
has been subjected to numerous investigations. Chromic
chloride, cupric chloride, aurous chloridecarbonyl and
silver bromide were the halides most thoroughly investigated.
The Grignard reagents studied were those from bromobenzene,
benzyl chloride, α-bromonaphthalene, cyclohexyl bromide and
the butyl bromides; the yields of the R-R compounds vary
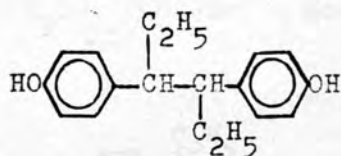from 25 to 100%.

To appreciate the tremendous effect of small quantities
of metallic halides, the following facts must be borne in
mind.

Metallic halides such as cobaltous chloride, nickel
chloride, ferric chloride do not react with aryl halides,
Arylmagnesium halides react with the above-mentioned metallic
halides to yield the biaryl compounds.

Thus phenylmagnesium bromide reacts with cobaltous

chloride to yield biphenyl. Furthermore it follows from scheme (6) that for each mole per cent of cobaltous chloride used, no more than two mole per cent of the Grignard reagent can be utilized and no more than one mole per cent of biphenyl is formed. Similar results were obtained by Gilman and Walter.[11]

Wilds and McCormack[12] considered that the continuously regenerated metal was in a favourable state of subdivision and activity. The first practical synthesis of the oestrogen hexoestrol (I) discovered by Dodds et al.[13] was reported independently by Peak and Short[14], and by Bernstein and Wallis[15]. This synthesis involved a Wurtz-type coupling of anethole hydrobromide (II) to hexoestroldimethyl ether (III).

$$HO-\underset{}{\bigcirc}-\underset{\underset{C_2H_5}{|}}{\overset{\overset{C_2H_5}{|}}{CH}}-CH-\bigcirc-OH$$

(I)

$$2CH_3O-\underset{}{\bigcirc}-\underset{\overset{C_2H_5}{|}}{CH}-Br + 2M \longrightarrow H_3CO-\underset{}{\bigcirc}-\underset{\underset{C_2H_5}{|}}{\overset{\overset{C_2H_5}{|}}{CH}}-CH-\bigcirc-OCH_3 + 2MBr$$
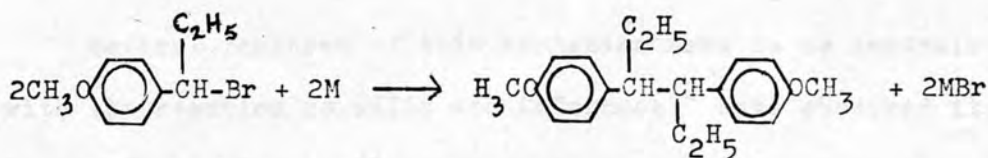
(II)   (III)

The yield of the meso-isomer of hexoestroldimethyl ether by this synthesis was 15-20% using metals such as magnesium and sodium, and somewhat lower (6%) employing a Grignard reagent such as methylmagnesium iodide[16]. In 1943 Kharasch and Kleiman[17] described an improved Grignard coupling procedure using phenylmagnesium bromide, in the presence of a catalytic

amount of cobaltous chloride, giving a 42% yield of the ether (III). Wilds and McCormack studied this catalysed Grignard synthesis of hexoestrol in some detail and have investigated the effect of the Grignard r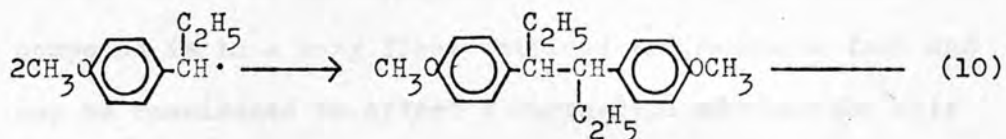eagent. The mechanism proposed by Kharasch and his coworkers, applied to the coupling reaction of anethole hydrobromide in the presence of phenylmagnesium bromide, is as follows:

$$C_6H_5MgBr + CoCl_2 \longrightarrow C_6H_5CoCl + MgBrCl \quad\text{———— (7)}$$

$$2C_6H_5CoCl \longrightarrow C_6H_5 \cdot C_6H_5 + 2CoCl \cdot \quad\text{———— (8)}$$

(9)

(10)
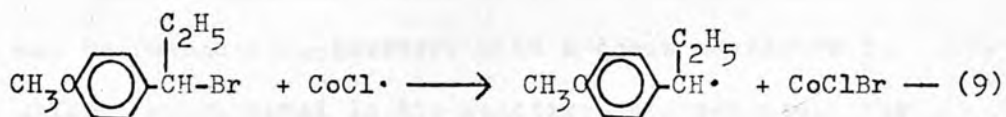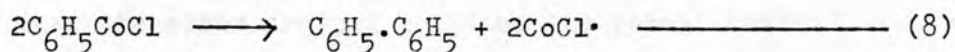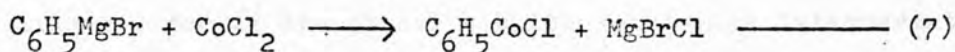
Several features of this mechanism seem to be inconsistent with the reaction as Wilds and McCormack[12] have observed it. In the first place, all attempts to prepare organocobalt compounds as postulated in equation (7) have indicated these to be unstable compounds, decomposing at once to metallic cobalt and the coupling or disproportionation products of the organic group. Secondly, there is no experimental evidence to indicate the stable existence of the cobaltous subhalide proposed as the reactive intermediate in equation(8). To be sure, each of these might be postulated as possible inter- mediates in the reaction, but it seems certain that they

would be very short-lived. Some catalytic activity was
retained by the Grignard-cobaltous chloride mixture after
standing at room temperature, for several days or even
weeks. This seems incompatible with the above mechanism,
since equations (7) and (8) should proceed in the absence
of anethole hydro-bromide and the reactive intermediates
would decompose to give metallic cobalt. In addition,
the organic product formed in reaction (8) presents a
dilemma, for if the phenyl cobaltous chloride intermediate
decomposed to give the radical CoCl•, it might be expected
that the other product would be the phenyl radical.

These facts and others which will be presented below
can be reconciled, however, with a chain mechanism in
which cobalt metal is the reactive intermediate. The
cobalt formed by decomposition of the unstable organocobalt
compound is in a very finely divided and reactive form and
may be considered to effect a Wurtz-type of reaction with
the anethole hydrobromide, very likely with the intermediate
formation of a free radical from the halide.

$$
\left[
\begin{array}{l}
2C_2H_5MgBr + CoCl_2 \longrightarrow MgBr_2 + MgCl_2 + (C_2H_5)_2Co \\
\angle(C_2H_5)_2Co\underline{7} \longrightarrow C_2H_6 + C_2H_4 + Co
\end{array}
\right] \quad\text{———————— (11)}
$$

$$
2CH_3O\!\!-\!\!\underset{}{\bigcirc}\!\!-\!\!\overset{\overset{C_2H_5}{|}}{CH}\!-\!Br + Co \longrightarrow CoBr_2 + 2CH_3O\!\!-\!\!\underset{}{\bigcirc}\!\!-\!\!\overset{\overset{C_2H_5}{|}}{CH}\!\cdot \quad\text{—— (12)}
$$

$$
2CH_3O\!\!-\!\!\underset{}{\bigcirc}\!\!-\!\!\overset{\overset{C_2H_5}{|}}{CH}\!\cdot \longrightarrow CH_3O\!\!-\!\!\underset{}{\bigcirc}\!\!-\!\!\underset{\underset{C_2H_5}{|}}{\overset{\overset{C_2H_5}{|}}{CH}\!-\!CH}\!\!-\!\!\underset{}{\bigcirc}\!\!-\!OCH_3 \quad\text{—— (13)}
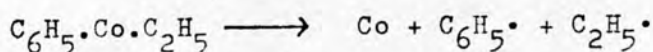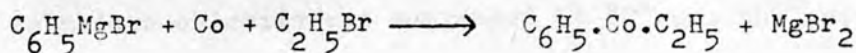$$
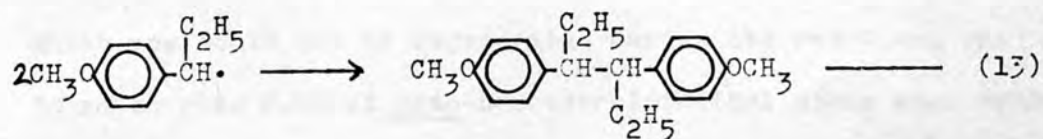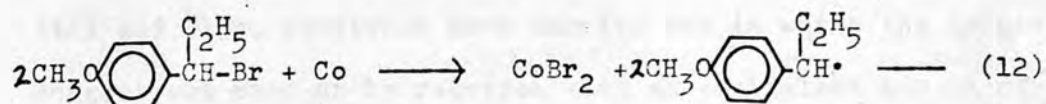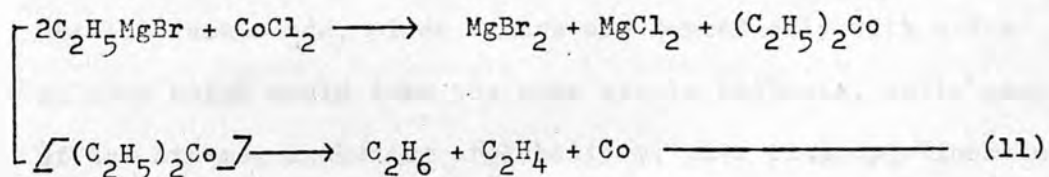
According to this mechanism the catalytic activity
of the Grignard-cobaltous chloride mixture would be retained
indefinitely, or as long as the cobalt metal remained in its
active, finely divided form. Kharasch and Fields[18] observed
differences in the stability of the catalyst prepared from
aryl and alkyl Grignard reagents. They reported that a
solution of phenyl magnesium bromide and cobaltous chloride
retained about 50% of its catalytic activity after refluxing
in ether solution for one and a half hours, while the catalyst
from methylmagnesium bromide was practically completely
destroyed under these conditions. The reaction of finely
divided cobalt metal with anethole hydrobromide (equation (12)
and (13)) is analogous to the earlier procedures[14,15], where
magnesium or sodium was used. It may be considered to
lie at one extreme of reactions of the Wurtz-type since cobalt
probably only removes the halogen to give a free radical
and does not react further to give an organometallic inter-
mediate at this stage. Kharasch and his coworkers have
pointed out that the product obtained in this type of reaction
are indicative of free radicals rather than unstable organo-
metallic compounds, since dimers are formed only with a few
halides which would form the more stable radicals, while most
of the others, including aryl halides, give disproportionation
products. In order to provide experimental confirmation for
(12) and (13), reactions were carried out in which the Grignard
reagent was used up by reaction with an equivalent amount of
cobaltous chloride. The resulting suspension of cobalt metal,
which now could not be regenerated during the reaction, was
found to give 8.5% of meso-hexoestroldimethyl ether when treated

with anethole hydrobromide. Although this yield is lower than
that obtained in the usual procedure, it can be attributed
to a less favourable state of subdivision of the cobalt
metal than when it is continually regenerated in the chain
reaction. In support of this view, the yield of (II) was
increased to 15% when the cobalt was first 'recycled' to
increase the state of subdivision of metal by allowing it to
react with an equivalent mixture of ethyl bromide and ethyl-
magnesium bromide prior to the addition of the anethole
hydrobromide.

The course of the reaction of anethole dibromide with
ethylmagnesium bromide in the presence of catalytic amounts
of cobaltous chloride might be considered to support the
proposed new mechanism. If cobaltous subchloride were the
reactive intermediate it might be expected to give to an
appreciable extent a free radical similar to that postulated
in equations (9) and (12), but containing a bromine atom,
resulting in a significant amount of coupling to give dimeric
or polymeric products. Actually anethole was obtained in this
reaction in 92% yield. This mechanism involving cobalt
metal can be used satisfactorily to explain most of the other
Grignard reactions, catalysed by cobaltous chloride, including
the dimeric reduction of certain ketones to pinacols and
related reactions.

On the basis of the instability of organocobalt compounds,
a somewhat different mechanism from that of Kharasch is
therefore proposed for cobalt-catalysed Grignard reactions.
This new mechanism involves the reduction of cobaltous chloride
to finely divided cobalt metal, which is the reactive inter-

mediate in the chain. Smith[19] prepared active cobalt by reduction of cobaltous chloride with sodiumnaphthalene radical ions and found that it did not react with ethyl bromide, this was confirmed by Frey[20]. However they have also observed that the addition of phenylmagnesium bromide to such a mixture produces an immediate evolution of ethane and ethylene. In another experiment an equimolar amount of the Grignard reagent was added to cobaltous chloride in tetrahydrofuran to produce dark brown, finely-divided cobalt metal. Addition of ethyl bromide to this mixture did not produce any significant gas evolution. However, when a second addition of Grignard reagent was made, an immediate evolution of gas occurred. Analysis of several samples of the evolved gases showed them to contain ethane and ethylene in a fairly constant ratio, so that Frey[20] concluded that cobalt metal is the active intermediate as proposed by Wilds and McCormack[12], but both Grignard and ethyl bromide must be present to effect reaction. Ethane, ethylene, biphenyl and ethylbenzene were qualitatively identified as products from cobalt-catalysed reaction of phenylmagnesium bromide and ethyl bromide. This led Frey[20] to suggest the following reaction scheme:

$$2C_6H_5MgBr + CoCl_2 \longrightarrow 2MgBrCl + (C_6H_5)_2Co$$

$$(C_6H_5)_2Co \longrightarrow Co + 2C_6H_5 \cdot$$

$$C_6H_5MgBr + Co + C_2H_5Br \longrightarrow C_6H_5 \cdot Co \cdot C_2H_5 + MgBr_2$$

$$C_6H_5 \cdot Co \cdot C_2H_5 \longrightarrow Co + C_6H_5 \cdot + C_2H_5 \cdot$$

$$2C_6H_5\cdot \longrightarrow C_6H_5\cdot C_6H_5$$

$$2C_2H_5\cdot \longrightarrow C_2H_4 + C_2H_6$$

$$C_6H_5\cdot + C_2H_5\cdot \longrightarrow C_6H_5\cdot C_2H_5$$
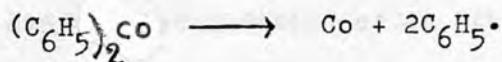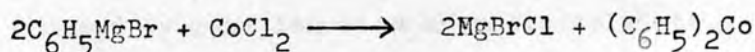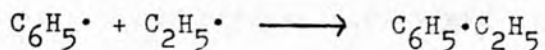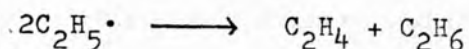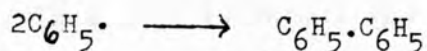
All the suggested reaction schemes involve the inter-
mediate formation of free radicals derived from organic
halides, but no systematic attempt has been made to deter-
mine their fate, in spite of the fact that the properties
of such radicals in solution are now well documented[21]. It
was considered[21] that the dilution of the reaction mixture
with an aromatic solvent should result in substitution
of the solvent by any free radical present. It is clear that
addition of cobaltous chloride to a Grignard reagent produces
a reactive species, which then reacts with the organic halide.
It was then expected that slow addition of a mixture of
cobaltous chloride and Grignard reagent to the halide in an
aromatic solvent, or the slow addition of the Grignard reagent
to a solution of halide in an aromatic solvent in which
cobaltous chloride was suspended, would result in the slow
production of radicals from halide, which would be readily
trapped by reaction with aromatic solvents.

Preliminary experiments by Davies, Hey and Tiecco[21],
showed that addition of an ethereal solution of methylmagnesium
iodide to a benzene solution of an aryl halide in which
cobaltous chloride was suspended at 80° was the most conve-
nient method for the study of radicals produced from halide,

since biaryls formed can only be derived from aryl halide.
Thus dropwise addition of methylmagnesium iodide in ether
solution to a stirred solution in benzene of p-bromotoluene,
in which 10 moles per cent of cobaltous chloride was suspended,
at 80° afforded a 16.6% yield of 4-methylbiphenyl, which almost
certainly arose by substitution of a p-tolyl radical derived
from the halide (p-bromotoluene) in the solvent benzene. It
was noteworthy that when cobaltous chloride is added to methyl-
magnesium iodide in ether, there is an immediate evolution
of gases, as the Grignard reagent reduces cobaltous chloride
to metallic cobalt; when this mixture was added to a solution
of p-bromotoluene in benzene at 25°, 4-methylbiphenyl was
obtained in 70% yield.

Kharasch and Fuchs[22] have shown that radical interchange
in certain systems of Grignard reagents and organic halides
occurs. Gilman and Jones[23] found that no interchange of
radicals occured, when the following mixtures of Grignard
reagents and organic halides were heated

a) $C_6H_5CH_2MgBr + C_6H_5Br$

b) $(C_6H_5)_3C\ MgCl + C_6H_5Br$

c) $C_6H_5MgBr + C_6H_5CH_2Cl$

d) $C_6H_5MgBr + (C_6H_5)_3C\ Cl$

e) $C_6H_5CH_2MgBr + (C_6H_5)_3C\ Cl$

To each of the above reaction mixtures carbon dioxide was

added finally to form carboxylic acids. In the literature
there are only three cases of radical interchange reported.
Prevost[24] has demonstrated that when ethylmagnesium bromide
reacts with 3-bromo-1-phenylpropene (C_6H_5-CH=CH-CH_2Br) there
is a definite increase in the amount of ethyl bromide present
in the mixture. Umnora[25] has demonstrated that the following
reaction take place when 2,4-dibromo-2, 4-dimethylpentan-3-one
is treated with phenylmagnesium bromide.

$$+ C_6H_5Br + MgBr_2$$
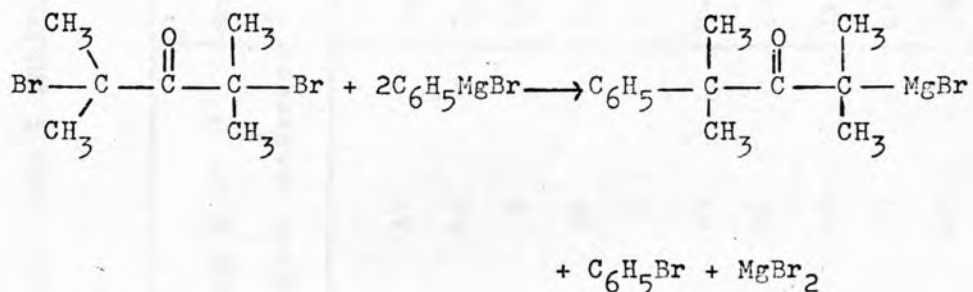
Urion[26] also found that an equimolar mixture of ethylmagnesium
bromide and cyclohexyl bromide, when allowed to react for
24 hours at room temperature showed a radical interchange.
The evidence was that when this mixture was hydrolysed after
standing, 12% of cyclohexane was obtained. However Kharasch
and Fuchs[22] could not agree with Urion. They observed
that when ethylmagnesium bromide was heated with cyclohexyl
bromide in ether solution, it gave a mixture of ethane,
ethylene, cyclohexane, and cyclohexene. Urion failed to
detect the first two of these compounds and mistook the mixture
of last two for pure cyclohexane according to them. The results
reported by Kharasch and Fuchs are in the following Table B.

Table B

Radical exchange reactions between Grignard Reagents and organic radicals in the presence of metallic halides.[22]

	Grignard Reagent	Organic halide or Hydrocarbon	Metallic halide	Mole % of halide condensed	Acid formed by radical exchange
(1)	*n-C_4H_9MgBr	C_6H_5Br	$CoCl_2$ (1%)	14	C_6H_5COOH (7%)
(2)	n-C_4H_9MgBr	C_6H_5Br	$CoCl_2$ (2%)	45	C_6H_5COOH (None)
(3)	*n-C_4H_9MgBr	(p)-$CH_3OC_6H_4$Br	$CoCl_2$ (1%)	8	$CH_3OC_6H_4$COOH (4%)
(4)	*CH_3MgBr	(p)-$C_6H_5C_6H_4$Br	$CoCl_2$ (1%)	22	(p)-$C_6H_5C_4H$ COOH (1%)
(5)	CH_3MgBr	Fluorene	$CoCl_2$ (1%)	-	Fluorenecarboxylic acid (None)
(6)	*CH_3MgBr	9-Chlorofluorene	$CoCl_2$ (1%)	99	9-Fluorenecarboxylic acid (10%)
(7)	CH_3MgBr	9-Bromophenanthrene	$CoCl_2$ (1%)	34	9-Phenanthrenecarboxylic acid (3%)
(8)	n-C_4H_9MgBr	(C_6H_5-)$_3$C Cl	$CoCl_2$ (1%)	60	Triphenylacetic acid (1.5%)
(9)	*C_6H_5MgBr	n-C_4H_9Br	$CoCl_2$ (1%)	60	n-Valeric acid (3%)
(10)	CH_3MgBr	C_6H_5CH=CHBr	$CoCl_2$ (1%)	85	phenylpropiolic acid (None)[a]
(11.)	CH_3MgBr	C_6H_5CH=CHBr	$FeCl_3$ (2%)	85	phenylpropiolic acid (None)[b]

Grignard Reagent	Organic halide or Hydrocarbon	Metallic halide	Mole % of halide condensed	Acid formed by radical exchange
(12) *n-C_4H_9MgBr	$(C_6H_5)_2C=\overset{\overset{\displaystyle Br}{\mid}}{C}-C_6H_5$	$CoCl_2$ (4%)	96	Triphenylacrylic acid (14%)[c]
(13) CH_3MgBr	$(C_6H_5)_2C=\overset{\overset{\displaystyle Br}{\mid}}{C}-C_6H_5$	$CoCl$ (3%)	57	Triphenylacrylic acid (32%)
(14) CH_3MgBr	$(C_6H_5)_2C=\overset{\overset{\displaystyle Br}{\mid}}{C}-C_6H_5$	$FeCl_3$ (3%)	37	Triphenylacrylic acid (13%)
(15) CH_3MgBr	$(C_6H_5)_2C=\overset{\overset{\displaystyle Br}{\mid}}{C}-C_6H_5$	$FeCl_2$ (3%)	37	Triphenylacrylic acid (19%)

a) Phenylpropiolic acid was absent but 1-phenylprop-1-ene (75%) and 1, 4-diphenylbutadiene (8%) were isolated. There was also a small amount of tar.

b) A 10% yield of 1-phenylprop-1-ene was isolated. This amount corresponds quantitatively to the amount of ω-bromostyrene consumed in the reaction. Excellent yields of the 1-phenylprop-1-ene may be obtained by allowing the reaction mixture to stand for 3-4 hours at $0°$.

c) The reaction mixture cooled to $0°$ was agitated for one hour. About 40% of triphenylethylene and 40% of polymer of triphenylacrylic acid were obtained, in addition to the triphenylacrylic acid.

These results indicated that in the absence of metallic halides, no radical interchange occurs. In the presence of cobaltous chloride the otherwise inert mixture of Grignard reagent and the organic halide reacts very rapidly[27] even at $0°$. In order to demonstrate any radical interchange it was therefore necessary to keep the reaction mixture between $0°$ and $-5°$. For example, when n-butyl bromide is treated with bromobenzene in the presence of cobaltous chloride, 3% of biphenyl is formed[28]. It has been shown[29] that when phenylmagnesium bromide is treated with either butyl or phenyl bromide in the presence of cobaltous chloride, 70-90% of the phenyl Grignard present is recovered as biphenyl. The 7-8% of benzoic acid formed, when the mixture of n-butylmagnesium bromide, bromobenzene and cobaltous chloride is treated with carbon dioxide, indicate a radical interchange of 7-8%. The divergence between two results that radical interchange occurred with triphenylbromoethylene, in the presence of one mole per

cent of cobaltous chloride, but no radical interchange occured with ω-bromostyrene is due to marked difference in reaction rates. However it appears probable that 1,4-diphenylbutadiene is the end product of two successive reactions. Firstly radical interchange may occur to give styrylmagnesium bromide, which may then react with cobaltous chloride in the presence of ω-bromostyrene to give 1,4-diphenylbutadiene.

4) VINYL RADICALS

(i) Stereochemistry in hydrogen atom transfer to equilibrated isomeric vinyl radicals:-

Vinyl radicals have recently received the attention of many workers, whose interest was focused on the configurational stability of such radicals, formed by hydrogen abstraction or halogen abstraction. Kampmier and Fantazier[30] investigated the decomposition of cis- and trans- α, β-dimethylpercinnamates
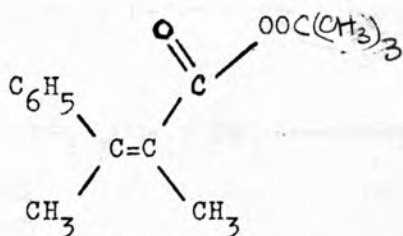
Cis-perester   Trans-perester
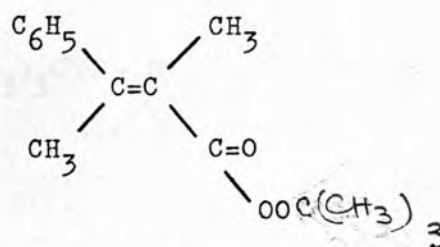
(IV)   (V)

under mild conditions at low temperatures (0° and 20° respectively), in order to avoid interconversion of isomers. Thermal de-composition of the cis and trans-peresters in cumene at 110° gave the following products respectively.

Carbon dioxide (61%, 92%)

Acetone (9%, 10%)

t-butyl alcohol (80%, 81%)

cis- (IV) and trans-2-phenyl but-2-ene (VII) (60%, 79%)

bicumyl (43%, 64%)

3,4-Dimethylcoumarin (13% from cis-perester only)

α, β-Dimethylcinnamic acids (1-2%) are formed with retention of stereochemistry. These acids are not decarboxylated under

the reaction conditions. These products clearly demonstrate
the formation of vinyl radicals in good yield. Both peresters give
the same ratio of cis to trans-2-phenylbut-2-ene (1.1-1.2).
The following scheme adequately describes the formation of all
products except 3,4-dimethylcoumarin, which is formed from
cis- but not from the trans-perester

$$RCO \cdot OOC(CH_3)_3 \longrightarrow RCO \cdot O \cdot + (CH_3)_3 CO \cdot$$

$$(CH_3)_3 CO \cdot \longrightarrow (CH_3)_2 CO + CH_3 \cdot$$

$$(CH_3)_3 CO \cdot + SH \longrightarrow (CH_3)_3 COH + S \cdot$$

$$RCO \cdot O \cdot \longrightarrow R \cdot + CO_2$$

$$R \cdot + SH \longrightarrow RH + S \cdot$$

$$2S \cdot \longrightarrow S-S$$

SH=Cumene, R=cis- or trans $C_6H_5-C(CH_3)=\overset{|}{\underset{CH_3}{C}}$
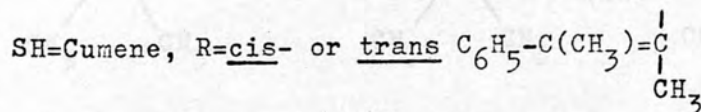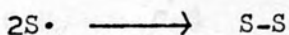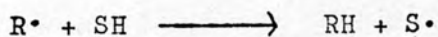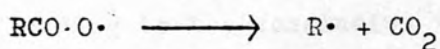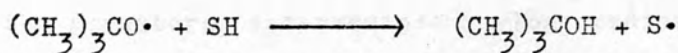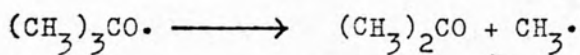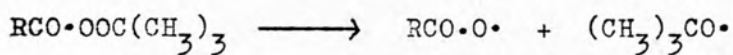
3,4-dimethylcoumarin arises via an intramolecular cyclization
of the cis-acyloxy radical.

$\cdot O$ — $C=O$ ... CH_3 ... CH_3

$\longrightarrow$

... CH_3 ... CH_3

$[-H\cdot]$

... CH_3
CH_3
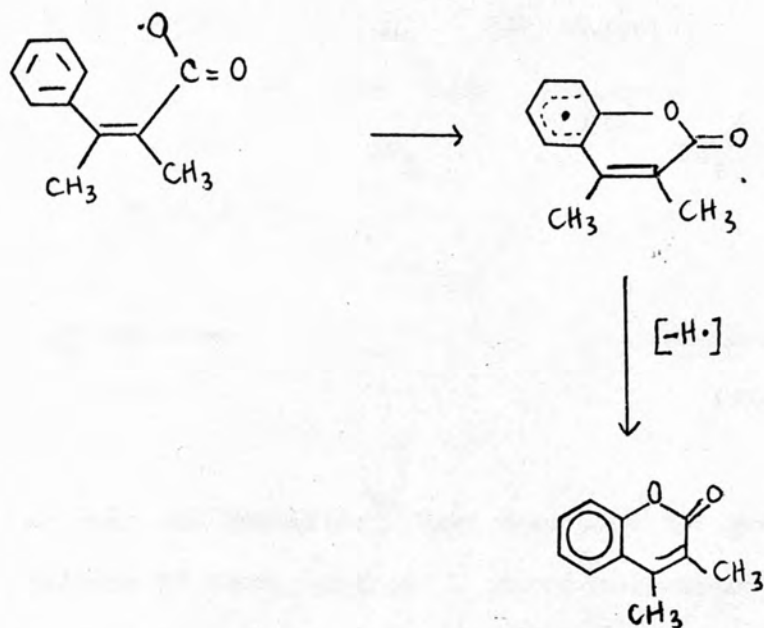
The peresters, intermediate acyloxy radicals and the olefins
are configurationally stable under the reaction conditions,
leading to the conclusion that the vinyl radicals equilibrate
more rapidly than they react with cumene.

$OOC(CH_3)_3$

C_6H_5 — $C=O$ C_6H_5 Cumene C_6H_5 — H

$C=C$ $\longrightarrow$ $\longrightarrow$ $C=C\cdot$ $\xrightarrow{\text{slow}}$ $C=C$

CH_3 — CH_3 CH_3 — CH_3 CH_3 — CH_3

cis-perester   cis-olefin

(IV)   (VI)
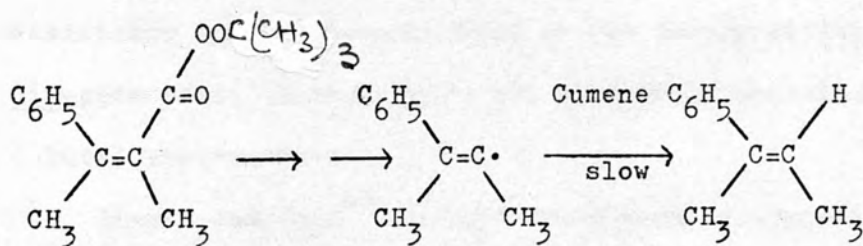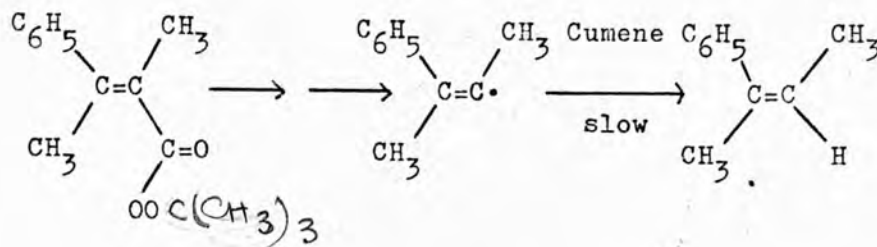
Trans-perester   trans-olefin

(V)   (VII)

Kampmier and Fantazier[30] have described the preparation and
products of decomposition of the stereoisomeric α, β -
unsaturated perester (IV) and (V) in cumene at 110°. However
the same workers[31] reported kinetic and scavenger studies,
which confirmed a rate-determining oxygen-oxygen homolysis
for the thermal decomposition of t-butyl cis- and trans- α,
β -dimethylpercinnamates. Activation parameters are essentially
identical for the two peresters, ruling out any anchimeric
assistance by the aromatic ring in the decomposition of the
cis-peresters. Both isomers are similar in behaviour to
t-butyl perbenzoate.

Singer and Kong[32] studied the thermal decomposition of cis- and
trans-t-butyl- α -methyl-percinnamate and α-phenylpercinnamate
systems; Decarboxylation of the acyloxy-radical to the vinyl
radical is the major pathway as evidenced by the high olefin
yields. It was seen that as the concentration of perester is
decreased, the olefin yields increase. This may simply be due
to a decrease in induced decomposition at lower perester con-
centrations. It is very clear that the same olefin ratio is obtained
from either the cis- or trans-perester in any one solvent indicating
equilibrium of the radicals before reaction with solvent. The high
cis-/trans- ratio is most easily explained by a faster rate of
capture of the cis- vinyl radical for steric reasons.

Cis-perester (VIII)   Trans-perester (IX)

Cis-acid   Trans-radical   Cis-radical
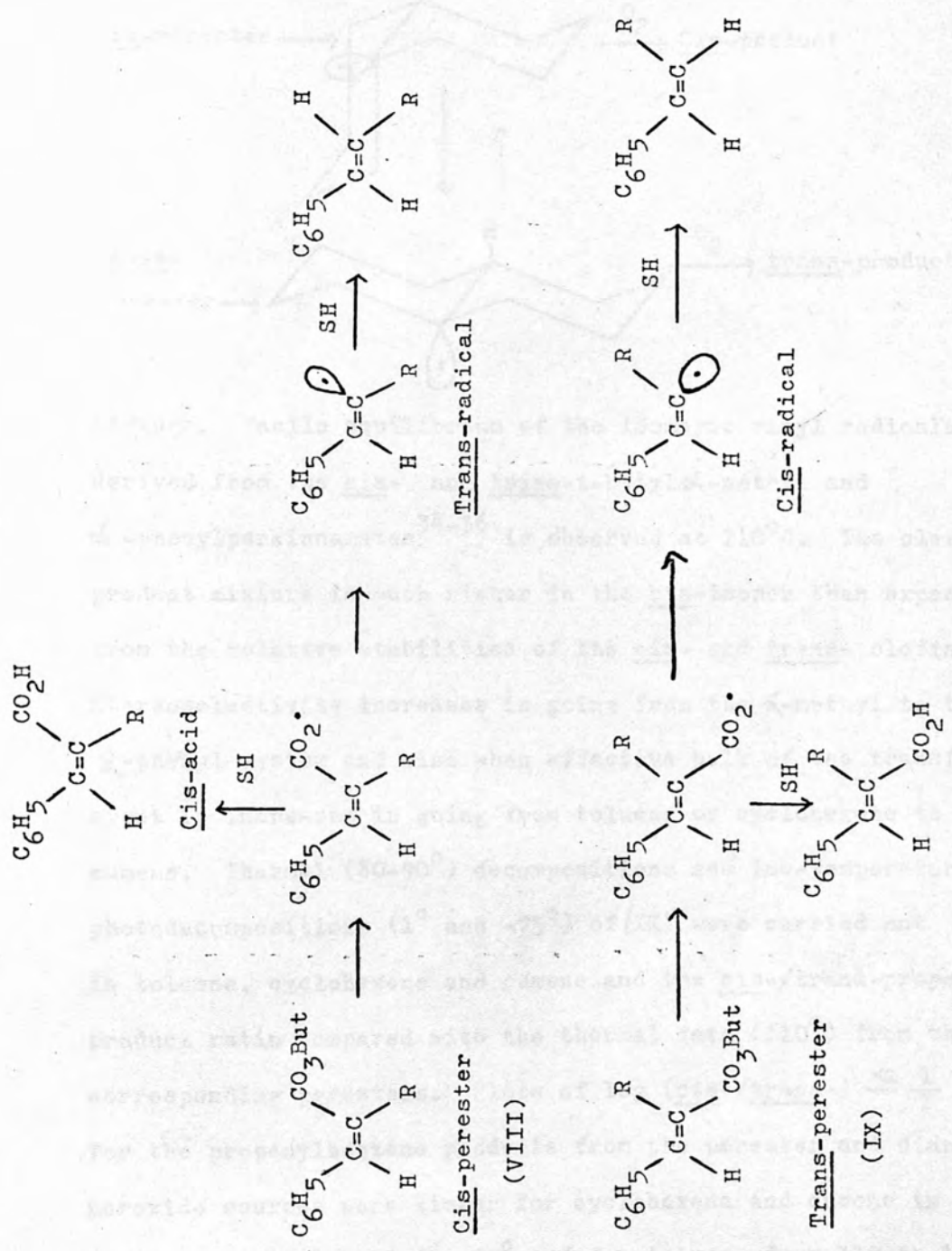
A similar effect was noted in studies of the 9-decalyl radical system[33], derived from thermal decomposition of cis- and trans- 9- carboxy-t-butylperoxydecalins, when a change from cyclohexene to cumene as the donor leads to an increase in the proportion of cis-decalin in the product
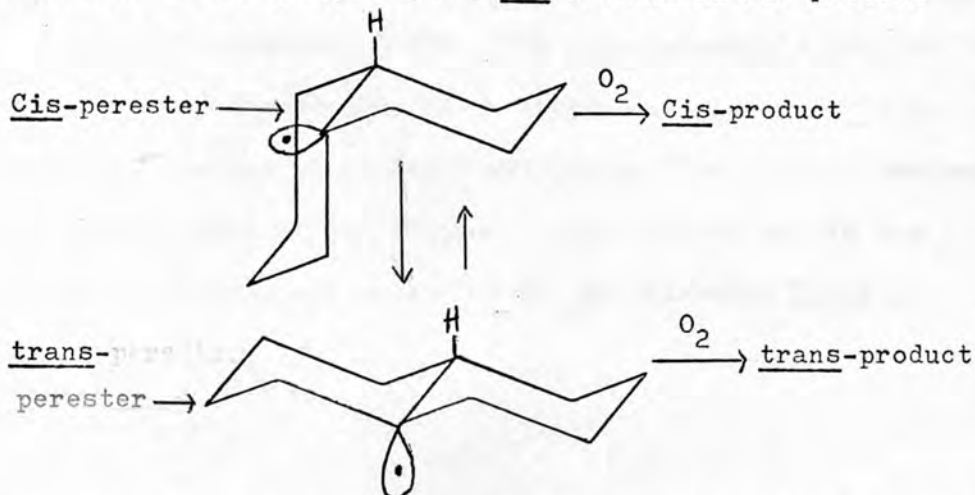
mixture. Facile equilibrium of the isomeric vinyl radicals derived from the cis- and trans-t-butylα-methyl and α-phenylpercinnamates[34-36] is observed at 110°C. The olefin product mixture is much richer in the cis-isomer than expected from the relative stabilities of the cis- and trans- olefins. Stereoselectivity increases in going from the α-methyl to the α-phenyl system and also when effective bulk of the transferring agent is increased in going from toluene or cyclohexene to cumene. Thermal (80-90°) decompositions and low-temperature photodecompositions (1° and -75°) of (IX) were carried out in toluene, cyclohexene and cumene and the cis-/trans-propenylbenzene product ratio compared with the thermal data (110°) from the corresponding peresters. Plots of log (cis-/trans-) $\frac{vs.}{}$ $\frac{1}{T}$ for the propenylbenzene products from the perester and diacyl peroxide sources were linear for cyclohexene and cumene in the temperature range 110 to -75° and for toluene from 110 to 1°.

From the slopes of the lines, the reactive stereoselectivity of these three solvents in hydrogen-atom transfer to the isomeric 1-methyl-2-phenylvinyl radical[37] were calculated.

Sargent and Browne[38] generated vinyl free radicals when they examined the reaction of sodium naphthalenide with cis- and trans-3-chlorohex-3-ene. The sole detectable product from either chlorohexene was a mixture of cis- and trans-hex-3-ene formed in at least 98% yield. The product analysis of several runs at two different temperatures and in two solvent systems are presented in the following Table C.

TABLE C

Yield of isomeric hex-3-enes from reaction of sodium naphthalenide
with cis- and trans- 3 chlorohex-3-enes

Solvent	Temp. (°C)	Product yield (%)			
		with cis-3-chlorohex-3-ene		with trans-3-chlorohex-3-ene	
		trans-hexene	cis-hexene	trans-hexene	cis-hexene
T.H.F. (Tetrahydrofuran)	0	69	31	85	15
T.H.F.	27	74	26	85	15
D.M.E. (1,2-dimethoxyethane)	0	56	44	82	18
D.M.E.	27	59	41	81	19

In all instances, <u>trans</u>-hex-3-ene predominates but the ratio of <u>cis</u>- to <u>trans</u>-hex-3-enes is decidedly a function of the configuration of the 3-chlorohex-3-ene employed. It was concluded that an initial charge-transfer reaction generates a non-linear vinyl radical which is capable of rapid inversion at the radical site, but the radical is trapped before complete equilibrium with its configurational isomer is achieved. The interconverting vinyl radicals might be trapped either by reduction to a configurationally stable carbanion (Path 1) or by hydrogen abstraction from the solvent (Path 2). The fact that <u>trans</u>-hex-3-ene, the thermodynamically more stable isomer predominates in the reaction mixture suggests
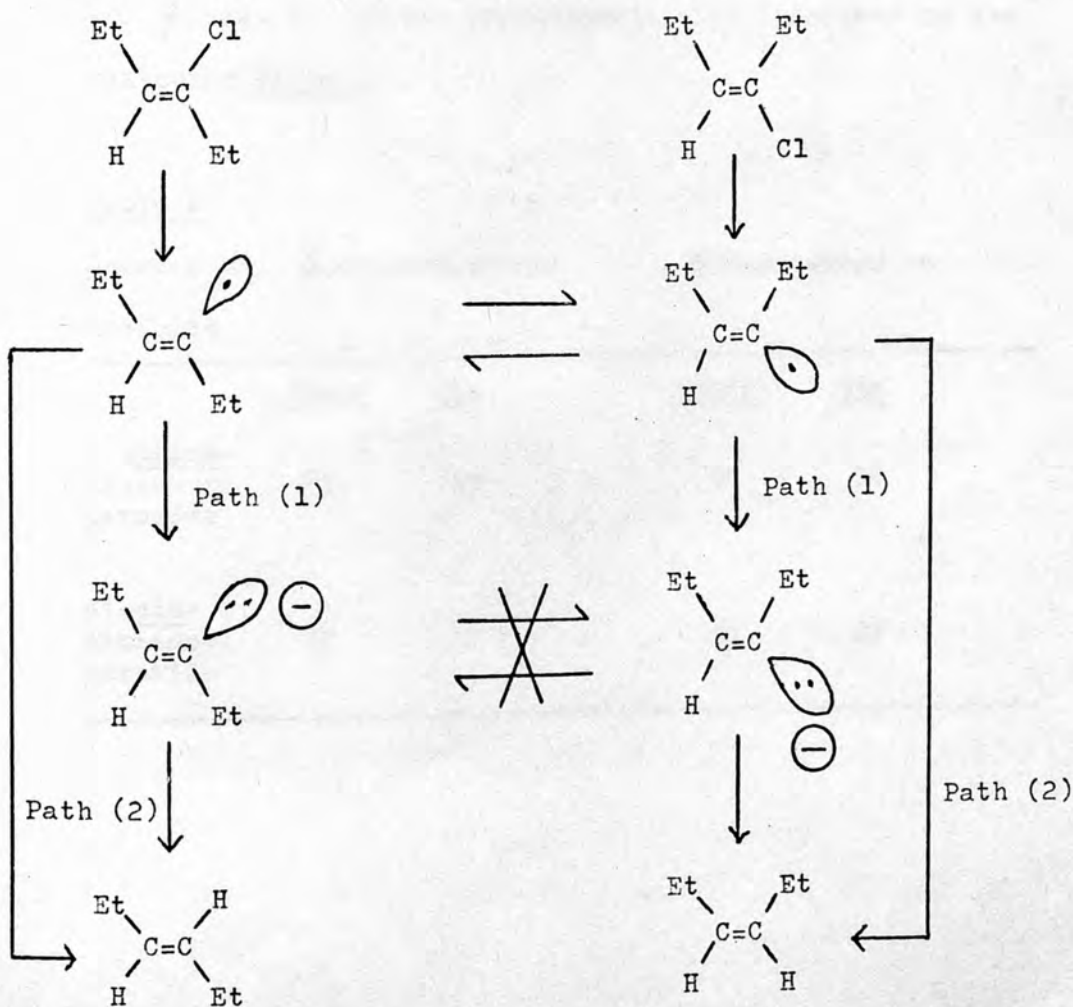
that the former pathway (1), because vinyl radicals generated by perester decomposition and trapped by reaction with hydrogen atom donors (e.g. cumene) have been found generally to lead to products, which relative to the equilibrium mixture, are markedly enriched in the thermodynamically less stable olefin. This is readily explained in terms of increased steric inter-action between the donor and acceptor molecules in the transition state for hydrogen atom donation to the trans-radical as compared with the cis-radical[39].

(ii) Styryl Radicals:

Simamura, Tokumaru and Yui[40] generated styryl radicals from the decomposition of cis- and trans- cinnamoyl peroxide in boiling carbon tetrachloride and bromotrichloromethane, under nitrogen. The reactions gave β-cis- and trans- chlorostyrenes and β-cis- and trans- bromostyrenes, as described in the following Table D

Table D

Sources of β-chlorostyrenes β-bromostyrenes

Radicals	Trans	Cis	Trans	Cis
di-trans-cinnamoyl peroxide	81	19	86	14
di-cis-cinnamoyl peroxide	82	18	73	27

Separate experiments showed that β-chloro and β-bromostyrene
do not undergo cis-trans isomerization under these experimental
conditions. Coumarin (21%) was formed in the decomposition
of di-cis-cinnamoyl peroxide, in each of the two solvents
used, but not in the experiments with the trans peroxide:
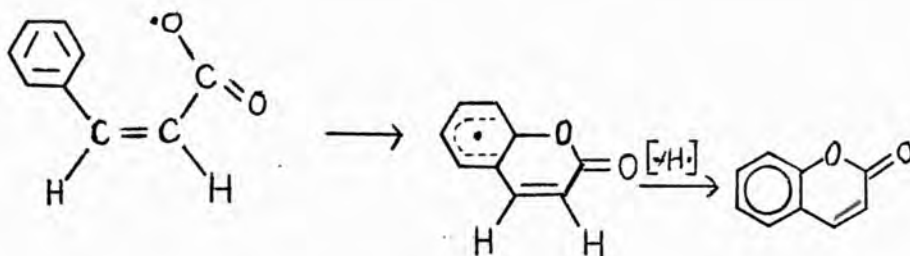
Further, the cis-peroxide gave the cis-, but not the trans-
cinnamic acid. The styryl radical, whether derived from the
cis or the trans- peroxide, abstracts a chlorine atom from
carbon tetrachloride, to give the same mixture of cis- and
trans-β-chlorostyrene. This shows that an equilibrium is
quickly established between the cis- and trans- styryl
radicals, in which the odd electron occupies an sp^2 hybrid
orbital. Alternatively a chlorine atom is abstracted before
a common intermediate radical of linear configuration may be
involved, in which the hybridization has undergone change from
sp^2 to sp at the radical centre. The latter possibility is
ruled out, since in bromotrichloroethane the ratio of the cis-
and trans- bromostyrene formed is different in the experiments
with the cis- and trans- peroxides.

The ratio of trans- to cis-β-chlorostyrene formed is
expressed as $K \cdot \dfrac{k_t}{k_c} = 4.4$. K is the equilibrium constant and k_t
and k_c are the rate constants for trans- and cis- chlorostyrene,

formed in the reaction of cis- or the trans-peroxide in boiling
carbon tetrachloride. In the absence of any evidence available
for assessment of the equilibrium constant K, this value was
assumed to be unity, since it does not seem that the steric
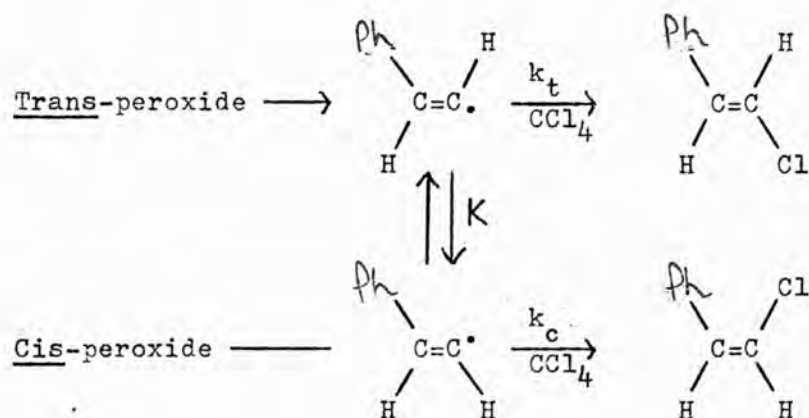
effect caused by the odd electron should be significantly
different between the two isomeric radicals. Then $\frac{k_t}{k_c} = 4.4$
i.e. the trans-styryl radical abstracts a chlorine atom
about four times as quickly as the cis-radical does, suggesting
that in the cis-radical the phenyl group sterically hinders the
abstraction reaction.

The fact that the ratio of trans- to cis-β-bromostyrene
formed the trans-peroxide (86:14) is larger than that for the
cis-peroxide (73:27), which is in turn smaller than the ratio
(81:19) in which the isomeric β-chlorostyrenes are invariably
formed, indicates that contrary to the case in carbon tetra-
chloride the abstraction by styryl radical of a bromine atom from
bromotrichloromethane proceeds at a rate comparable with, but
slightly higher than the rapid cis-trans isomerization between
the isomeric styryl radicals. This is probably due to weakness
of the C-Br bond in comparison with the C-Cl bond, and is in

keeping with the fact that the homolytic addition of
bromotrichloromethane to olefins take place much more readily
than that of carbon tetrachloride and without the formation
of appreciable quantities of telomeric products[41].

(iii) Homolytic Aromatic Substitution with Cyclohex-1-enyl

   Radicals:-

Spagnolo and Tiecco[42] generated cyclohex-1-enyl radicals from
the peroxide of cyclohexene-1-carboxylic acid (X).
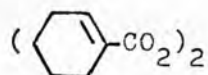
(X)

The decomposition of peroxide (X) in benzene at 80° for 24 hours
afforded, cyclohexene-1-carboxylic acid (XI), cyclohexene (XII),
1-phenylcyclohex-1-ene (XIII) and some carbonyl-containing
polymeric materials.
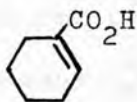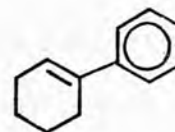
(XI)   (XII)   (XIII)

Decomposition of (X) in cumene gave bicumyl as the major product,
together with cyclohexene and cyclohexene-1-carboxylic acid,
gas-chromatographic analysis of this reaction mixture showed
that it contained small amounts of three isomeric 1-isopropyl-
phenyl cyclohexenes (XIV, XV, XVI).
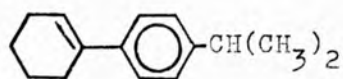
(XIV)
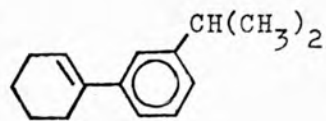
(XV)
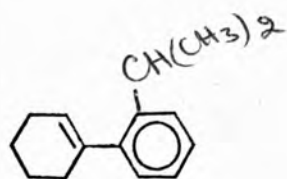
(XVI)

Similar experiments were also carried out with other mono-substituted benzenes, as the solvents and in all cases mixtures of isomers were obtained. Generally the reaction was:-

(X)   (o,m,p)

$X = -CH_3$, $-C(CH_3)_3$, $-OCH_3$
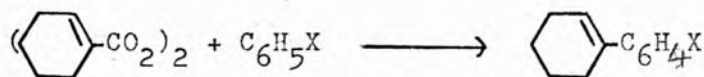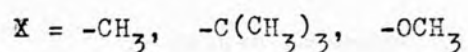
The reactivities of the benzene derivatives C_6H_5X relative to benzene ($\frac{X}{H}$K) toward substitution by cyclohex-1-enyl radicals, were determined by competitive experiments in which equimolar C_6H_5X/benzene mixtures were allowed to compete for cyclohex-1-enyl radicals.

Table E

Isomer ratios and relative reactivities in homolytic aromatic cyclohex-1-enylation[(a)].

Aromatic Solvent	1-Arylcyclohex-1-enes			$_H^x K$
	o-	m-	p- (%)	
C_6H_5X				
$C_6H_5CH_3$[(b)]	67	——— 33 ———		1.2
$C_6H_5C(CH_3)_3$	20	60	20	0.75
$C_6H_5OCH_3$	68	16	16	1.5

(a) Determined by Gas-liquid-chromatography.

(b) m- and p- isomers were not resolved under experimental conditions used. Bibenzyl was also present.

The values reported in the Table E may be taken as a clear indication of the homolytic nature of the aromatic substitution, since they are not very much different from the corresponding values reported for substitution by phenyl radicals[21,43], and suggest that no unusual properties are associated with cyclohex-1-enyl radicals in homolytic aromatic substitution.

5) SILVER CATALYZED OXIDATIVE DECARBOXYLATION OF ACIDS

(i) The Role of Silver (II):-

Transition metal ions are useful redox agents. The combination of ferrous ion and hydrogen peroxide, a reagent discovered by Fenton in 1894, was to be used in organic chemistry. Redox initiators are useful for the production of radicals in aqueous systems, and are particularly valuable as catalysts for low temperature emulsion polymerization.

Silver (I) is involved in an efficient catalysis of the oxidative decarboxylation of acids by peroxydisulphate ion in aqueous solution. The readily available peroxydisulphate ion, $S_2O_8^{2-}$ is an excellent and versatile oxidant for a variety of organic and inorganic compounds[44,45,46]. Despite the relatively high oxidation potential for the half reaction (14) many oxidations by peroxydisulphate do not proceed at a convenient rate at ambient temperatures. This can be largely attributed to the rate limiting homolysis given by equation (15)[44-47]

$$S_2O_8^{2-} \text{ (aq.)} + 2e \longrightarrow 2SO_4^{2-} \text{ (aq.) } E_o = 2.01V \quad \text{---- (14)}$$

$$S_2O_8^{2-} \longrightarrow 2SO_4^{-}\cdot \quad \text{---- (15)}$$
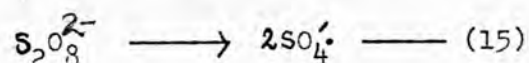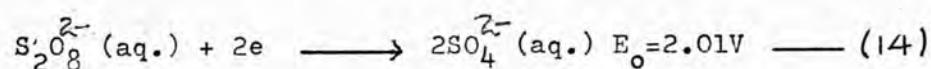
The decomposition of the peroxydisulphate ion, however, is accelerated by strong mineral acids, as well as by trace metal ions[44,45]. The oxidative decarboxylation of acids given by equation (16) is a convenient probe for the investigation of the mechanism of such oxidations[48].

$$RCO_2^{-} \longrightarrow RCO_2\cdot + e \quad \text{------ (16)}$$
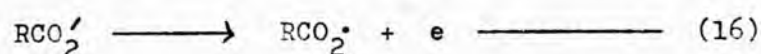
The noncatalyzed decarboxylation of salts of carboxylic acids
by peroxydisulphate was originally investigated by Fichter and
coworkers.[49] Tanner and Osman[50] have evaluated the relative rates
of electron transfer (equation 17) from various ring-substituted
phenyl acetates to sulphate ion-radical presumed to be the
active species in these oxidations[51].

$$RCO_2' + SO_4'\cdot \longrightarrow RCO_2\cdot + SO_4^{2-} \quad\quad (17)$$
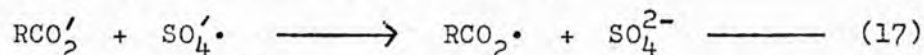
Anderson and Kochi[52] found that the oxidative decarboxylation
of a series of acids by peroxydisulphate ion is markedly acce-
lerated by silver ion. The stoichiometry of oxidative decar-
boxylation that given in equation (18)

$$2RCO_2H + S_2O_8^{2-} + 2HY \xrightarrow{Ag(I)} 2RH + 2CO_2 + 2H^+ + Y_2 + 2SO_4^{2-}$$
HY = Hydrogen-donor $\quad\quad (18)$
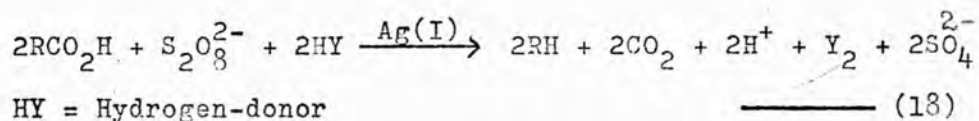
The stoichiometry of the oxidation changed as the concentration
of the acid decreased and it approached that given in equation (19)
at the lower limit.

$$RCO_2H + S_2O_8^{2-} \xrightarrow{Ag(I)} \left[R^+\right]_{ox} + H^+ + CO_2 + 2SO_4^{2-} \quad\quad (19)$$
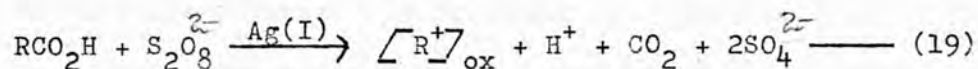
Product studies and kinetic comparisons pointed directly to
the involvement of Ag(II) and not of sulphate radical anions,
or hydroxyl radicals as the prime reactive intermediates, Ag(II)
species are formed by the rate-limiting oxidation of Ag(I)
by peroxydisulphate.

Scheme: Silver (I) catalyzed Decarboxylation.

$$Ag(I) + S_2O_8^{2-} \longrightarrow Ag(II) + SO_4^{2-} + SO_4^{-}\cdot \quad \text{——— (20)}$$

$$Ag(I) + SO_4^{-}\cdot \longrightarrow Ag(II) + SO_4^{2-} \quad \text{——— (21)}$$

$$Ag(II) + RCO_2H \longrightarrow Ag(I) + RCO_2\cdot + H^+ \quad \text{——— (22)}$$

$$RCO_2\cdot \longrightarrow R\cdot + CO_2 \quad \text{——— (23)}$$

$$R\cdot + HY \longrightarrow RH + Y\cdot \quad \text{——— (24)}$$

$$R\cdot + Ag(II) \longrightarrow [R^+]_{ox} + Ag(I) \text{ etc. ——— (25)}$$

$[R^+]_{ox}$ = alkene, alcohol, ester
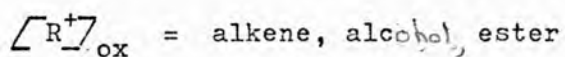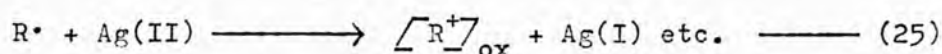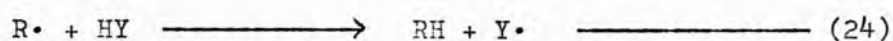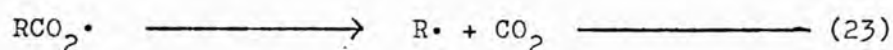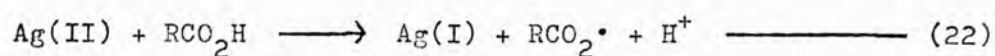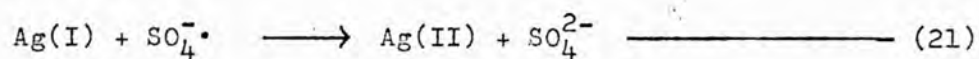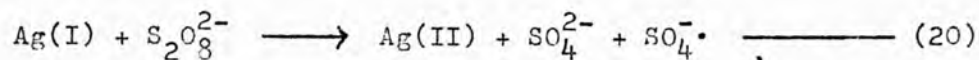
Direct and rapid oxidation of the carboxylic acid group by
Ag(II) in a fast subsequent step generates an acyloxy-radical,
which then fragments to an alkyl radical and carbon dioxide.
Products were derived by oxidation of alkyl radical by silver
species as well as by hydrogen transfer to the solvent.
Various facts of this mechanism will be taken into account in
the following discussion.

Initiation and Formation of Silver (II) Species:-

The rate limiting oxidation of silver (I) by peroxydisulphate
(20) following in quick succession by a second oxidation by
the sulphate ion-radical (21) has been considered at length[44,45].
The sequence (27) distinguished from the formation of a silver (III)

species by a two equivalent oxidation (26), which undergo rapid proportionation[53] with Ag(I) (27). The equilibrium constant for the latter reaction lies far to the right, although it has only been studied in concentrated solution of mineral acids[54], the only medium in which these high oxidation states of silver are stable.

$$Ag(I) + S_2O_8^{2-} \longrightarrow Ag(III) + 2SO_4^{2-} \qquad\qquad (26)$$

$$Ag(III) + Ag(I) \rightleftharpoons 2Ag(II) \qquad\qquad\qquad (27)$$
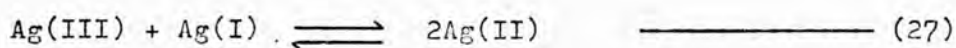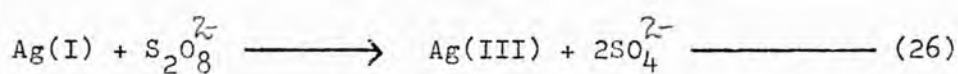
Silver (II) species as metastable intermediate.

The detection of a silver (II) species as a transient intermediate during the silver (I) catalysed decarboxylation with peroxydisulphate was attempted by e.s.r. and absorption spectral techniques. These physical methods were used in conjunction with product studies in which the decarboxylation of acids by the silver-peroxydisulphate procedure was compared with that employing well-characterized silver (II) complexes. Silver (II) complexes were generated in solution separately by the oxidation of 0.01M. Silver (I) nitrate and perchlorate with 0.1M peroxydisulphate in concentrated (3-5M) mineral acid solutions. Ag(II) species formed in nitric acid absorbed at 381 nm whereas those formed in perchloric acid at 461 nm. The visible absorption spectra were the same as those obtained by ozonolysis of silver (I) complexes[55]. The variation in the spectra obtained for silver (II) species in the presence of various counter ions (e.g. nitrate and perchlorate) has been attributed to the formation of rather stable inner sphere complexes. The peroxydisulphate oxidation of silver (I)

generate silver (II) in quantitative yield, based on extinction coefficients reported by Kirwin[55]. Attempts to observe Ag(II) species spectrally in the absence of concentrated solutions of mineral acids were unsuccessful. Nitrogen-containing ligands such as α-picolinic acid and α, α'-bipyridyl, however, are known to stabilize Ag(II) species. The formation of the bisbipyridylsilver (II) complex from the oxidation of the silver (I) complex with peroxydisulphate can be examined kinetically[56]. This silver (II) complexes was not a sufficiently strong oxidant to oxidize n-butyric acid readily at 25°C and the kinetics of its formation under these conditions were unaffected by the presence of n-butyric acid. Carboxylic acids, however, would be oxidatively decarboxylated by these aminesilver (II) complexes in a stoichiometric manner at higher temperatures. The products obtained were essentially the same as those formed by the catalytic decomposition of peroxydisulphate with silver (I) described above[57].

Silver(II) species and the Decarboxylation of Acids:

It has been proposed that it is the silver(II) species, which is the agent directly responsible for the decarboxylation of the acid. It is therefore a moot point whether such oxidation occurs _via_ hydrogen atom transfer directly from the acid (28) or _via_ prior incorporation of the acid into the Ag(II) species as a ligand (29) followed by homolysis of the silver-oxygen bond (30).

$$RCO_2H + Ag(II) \longrightarrow \left[RCO_2 \cdots H \cdots Ag \right]^{2+} \longrightarrow$$

$$RCO_2{}^{\bullet} + H^+ + Ag(I) \quad\text{——————}\quad (28)$$

$$RCO_2H + Ag(II) \rightleftharpoons RCO_2Ag(II) + H^+ \text{\textemdash} (29)$$

$$RCO_2Ag(II) \longrightarrow RCO_2\cdot + Ag(I) \text{\textemdash} (30)$$
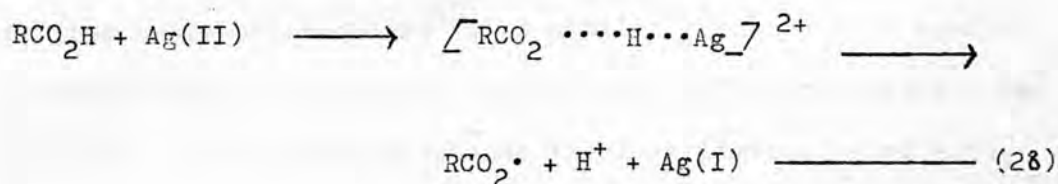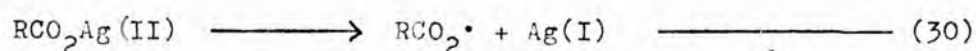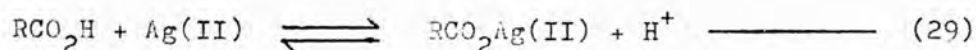
In either case the acyloxy radical is known to undergo rapid fragmentation with liberation of carbon dioxide and an alkyl radical (31).

$$RCO_2\cdot \longrightarrow R\cdot + CO_2 \text{\textemdash} (31)$$

The absence of significant differences in the rates of decarboxylation of pivalic, isobutyric and n-butyric acids militates against the simultaneous fission of the alkyl-carbonyl bond in the decarboxylation step, as formulated in (32).

$$RCO_2H + Ag(II) \longrightarrow R\cdot + CO_2 + H^+ + Ag(I) \text{\textemdash} (32)$$
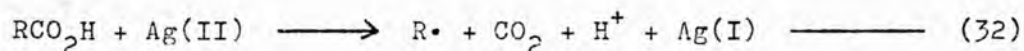
Qualitatively acids are decarboxylated more readily by the silver-peroxydisulphate method than by Pb(IV), which in turn effects decarboxylation at lower temperatures than Co(III), while decarboxylation by Mn(III) occurs at the highest temperatures of all and shows the greatest selectivity.

Decarboxylation by Ce(IV) is induced photochemically and shows no selectivity. In the last case sufficient energy is provided by irradiation at $3500^\circ A$ to effect homolysis to acyloxy-radicals and a driving force arising from multibond cleavage is presumably not required[58]. A similar photochemical process probably occurs in decarboxylation with Tl(III) complexes. On this basis it is postulated that the decarboxylation of acids by Ag(II) should be highly exothermic. It is easily demonstrable

that Ag(II) formed in strong mineral acid solutions is capable
of inducing rapid decarboxylation of acids, although the
stoichiometry of the oxidation is not yet clear. Moreover,
even those Ag(II) complexes, stabilized with α, α'-bipyridyl
and α-picolinato- ligands are capable of inducing ready oxidative
decarboxylation of acids. Finally Ag(III) species have been
widely invoked as intermediates in the silver(I) catalysed
reactions of peroxydisulphate[59,45] and it is conceivable that
Ag(III) is directly involved in the two-equivalent oxidation of
acids as in (33)

$$RCO_2H + Ag(III) \longrightarrow \underline{/R^+\underline{/}}_{ox} + CO_2 + H^+ + Ag(I) \quad\text{——}\quad (33)$$
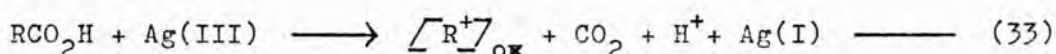
The mechanism proposed involving the one-equivalent oxidation
of acids by Ag(II) demands that alkyl radicals are intermediates.
Chemical and kinetic evidence can also be used to support alkyl
radicals as intermediates in these reactions. Direct observation
of alkyl radicals by their electron-spin resonance spectra have
been reported in the related decarboxylations by Pb(IV) and
Ce(IV)[48,60].

Product formations:- The increase in yield of alkane with increasing
concentration of carboxylic acid is related to hydrogen abstraction
predominantly from the α-position of the acid (34).

$$R\cdot + H_2OC\text{-}C\text{-}H \longrightarrow RH + H_2OC\text{-}C\cdot \quad\text{——}\quad (34)$$
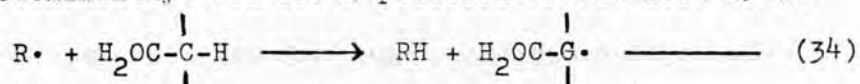
As the concentration of carboxylic acid is lowered the alkyl
radical increasingly suffers oxidation and alkenes and alcohols
become predominent products. It is not clear whether this
oxidation of alkyl radical is effected by Ag(II) or sulphate
ion radical (35) or by induced decomposition of peroxydisulphate (30)

$$R\cdot + SO_4^{'}\cdot \diagup Ag(II) \diagdown \longrightarrow \diagup R^+ \diagdown_{ox} + SO_4^{2-} \diagup Ag(I) \diagdown \quad\text{------ (35)}$$

$$R\cdot + S_2O_8^{2-} \longrightarrow ROSO_3^{'} + SO_4^{'}\cdot \text{ etc} \quad\text{------ (36)}$$
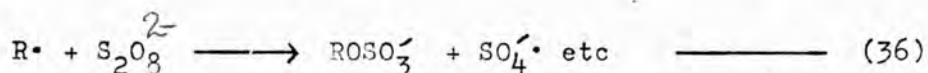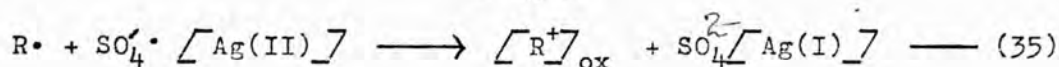
The Role of Sulphate ion Radical:-

Sulphate ion radicals have been included as intermediates
in a variety of catalysed as well as uncatalysed reactions of
peroxydisulphate. They have been invoked for the oxidation of
acids in alkaline media by the Fichter procedure[61], have shown
that the products obtained on persulphate oxidation of aliphatic
and aromatic acids are similar to those formed by anodic oxidation,
although some caution must be exercised in the comparison of a
heterogeneous reaction involving an electrode surface and a
homogemeous chemical method for decarboxylation. However it
is well established that the behaviour of sulphate ion radical
is highly sensitive to pH, especially with respect to electron-
transfer processes (37) and (38)[52].

$$RCO_2^{'} + SO_4^{'}\cdot \longrightarrow RCO_2\cdot + SO_4^{2-} \quad\text{------ (37)}$$

$$SO_4^{'}\cdot + OH^- \longrightarrow SO_4^{2-} + OH\cdot \quad\text{------ (38)}$$
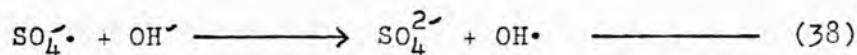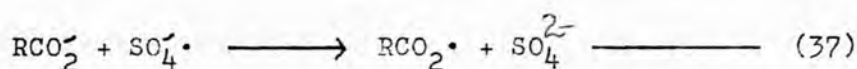
Under Anderson and Kochi's[52] conditions (thermally at $60^{\circ}C$),
there is no need to involve sulphate ion radicals directly in
decarboxylation processes such as (39), since sulphate ion radicals
generated by thermolysis of peroxydisulphate (15) are ineffective
in inducing decarboxylation in the absence of silver (I).

$$RCO_2H + SO_4^{'}\cdot \longrightarrow RCO_2\cdot + HSO_4^{'} \quad\text{------ (39)}$$
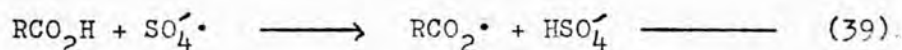
(ii) Alkylation by Decarboxylation of Acids:-

A new method of homolytic alkylation of heteroaromatic bases
has been described by Minisci[63], in which silver-catalyzed oxidative
decarboxylation of acids by peroxydisulphate is used as a source
of alkyl radicals. The nucleophilic character of alkyl radicals
permits the ready and selective alkylation of protonated hetero-
aromatic bases. This new homolytic alkylation process, which
is particularly useful from a synthetic point of view since it
permits the introduction of a large variety of primary, secondary
and tertiary alkyl groups in good yields and, with high selectivity,
under simple experimental conditions. The catalytic action of
silver salt is interpreted according to the following redox
radical chain. The method is particularly noteworthy, because

$$2Ag^+ + S_2O_8^{2-} \longrightarrow 2Ag^{2+} + 2SO_4^{2-} \quad\quad\quad (40)$$

$$RCOOH + Ag^{2+} \longrightarrow R\cdot + CO_2 + H^+ + Ag^+ \quad\quad (41)$$
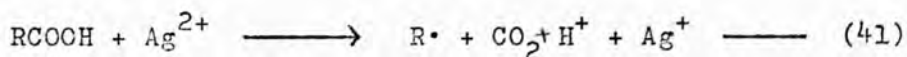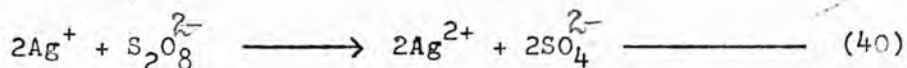
of good yields and the high selectivity, which arise from the
nucleophilic character of the alkyl radicals. Two redox
processes were used by Minisci[64].

(i) Cyclohexanone peroxide and ferrous sulphate.

$$CH_3OOC-(CH_2)_4-CH_2\cdot$$
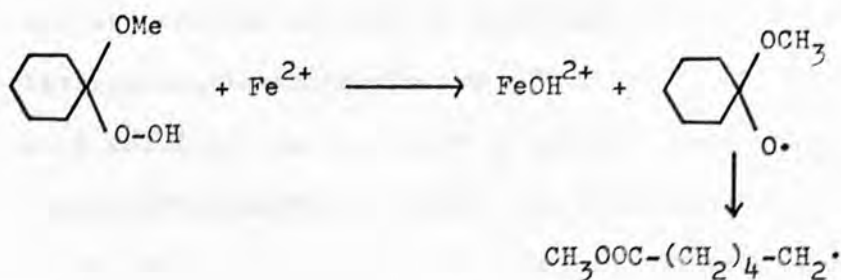
(XVII)

(ii) 2 methyl-3, 3-pentamethylene-oxazirane and ferrous sulphate: in this case the formation of the alkyl radical was explained by an analogous sequence[65]
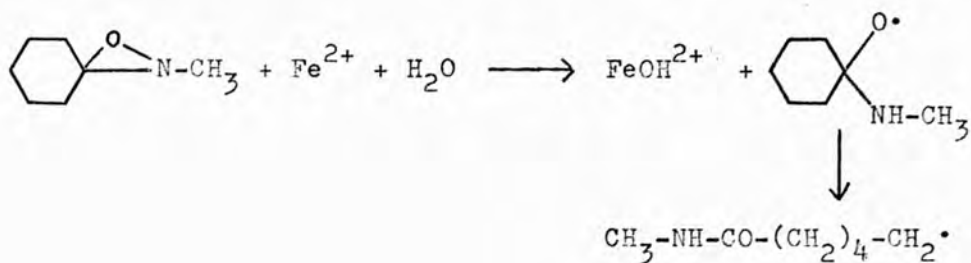
(XVIII)

while Minisci[66] showed a somewhat different pathway:
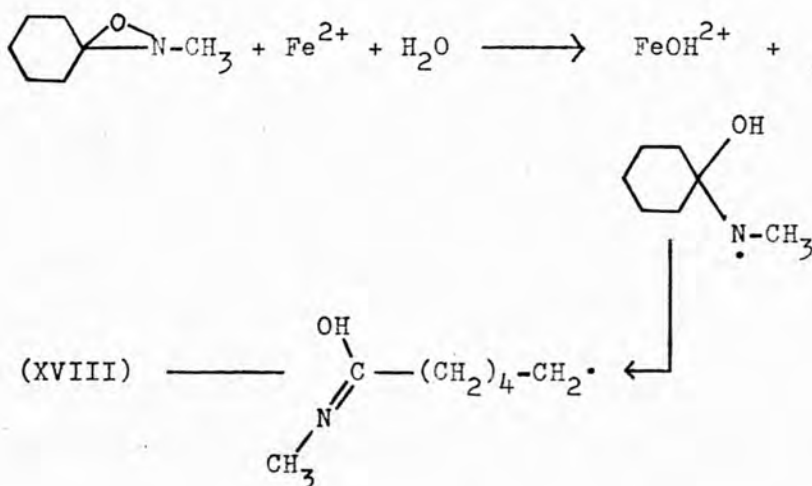
The synthetic interest arises from the easy availability of radical sources and simple experimental conditions. A number of heteroaromatic compounds are alkylated by both redox system in acid solution, in the cases of pyridine and quinoline, gas-liquid-chromatography showed the formation of 2- and 4- derivatives in 70-80% total yield. The reaction mechanism involves the redox chain.

$$R\cdot + \underset{}{\bigcirc}\overset{+}{N}H \longrightarrow \underset{}{\bigcirc}\overset{+}{N}H \quad (R=XVII \text{ or } XVIII)$$

$$\underset{}{\bigcirc}\overset{+}{N}H + Fe^{+++} \longrightarrow \underset{}{\bigcirc}\overset{+}{N}H + Fe^{++} + H^{+}.$$
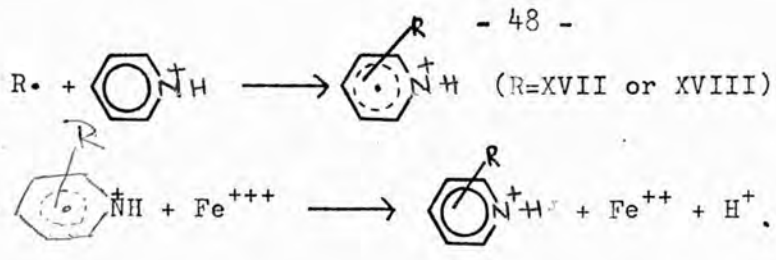
In the cases of pyridine, pyrazine and isoquinoline XIX, XX and
XXI, arising from dimerizing of the intermediate radical and
subsequent oxidation are isolated as by products: aromatic
compounds such as

(XIX)   (XX)

(XXI)
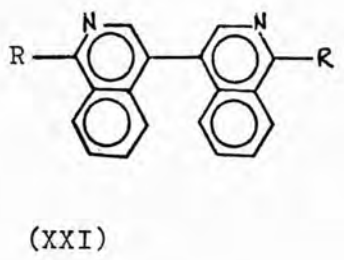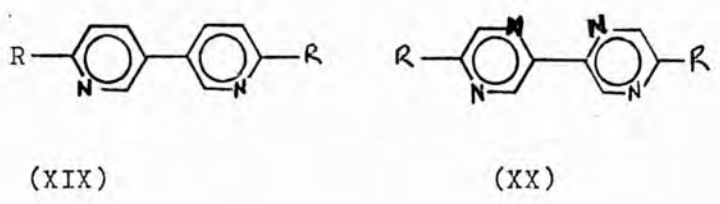
benzene and chlorobenzene, do not react under the same experimental
conditions in homogeneous medium, indicating the nucleophilic
character of this new type of radical alkylation. Addition of
the radical (XVII) to conjugated olefins in the presence of metal
salts has been studied by Minisci[67] and by Kochi and Rust[68], who
reported the reactivity of radical (XVII) to be higher with
butadiene and styrene than with olefins conjugated with electron
withdrawing groups, such as acrylonitrile or methyl acrylate owing
to the electrophilic character of the radical. Minisci[64]
indicated an opposite sequence, according nucleophilic character
to (XVII).

Two new syntheses of conclusions were correct:

(i) The radicals (XVII) and (XVIII), generated in the simultaneous presence of butadiene and an olefin conjugated with an electron-withdrawing group (X=CN, COOH, $COOCH_3$, $COCH_3$) give rise mainly to (XXII)

$$R\cdot + CH_2=CHX \longrightarrow RCH_2-\overset{\bullet}{C}HX$$

$$R-CH_2-\overset{\bullet}{C}HX + C_4H_6 \longrightarrow R-CH_2-CHX-C_4H_6\cdot$$

$$2R-CH_2-CHX-C_4H_6\cdot \longrightarrow (R-CH_2-CHX-C_4H_6-)_2$$
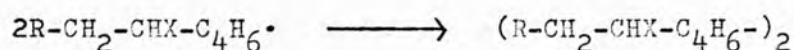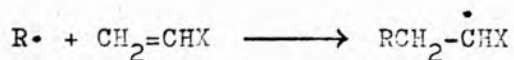
(XXII)

(ii) Catalytic amount of cupric sulphate in methanol oxidizes quantitatively the allylic radicals:

$$R-CH_2-CHX-C_4H_6\cdot + Cu^{++} \longrightarrow RCH_2-CHX-C_4H_6^+ + Cu^+$$

$$R-CH_2-CHX-C_4H_6^+ + CH_3OH \longrightarrow R-CH_2-CHX-C_4H_6-OCH_3 + H^+$$
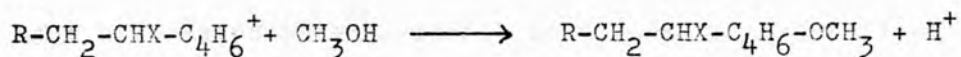
when X is carboxyl group an intramolecular reaction of the allylic cation takes place:

$$\underset{\underset{COOH}{|}}{R-CH_2-CH-C_4H_6^+} \longrightarrow \underset{\underset{CO\!-\!\!-\!\!-\!O}{|\qquad|}}{R-CH_2-CH-CH_2-CH-CH=CH_2}$$

$+ H^+$
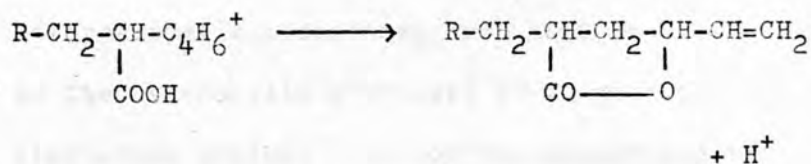
Analogously (XIII) and (XIV) were obtained with α-methyl-styrene instead of butadiene:

$$R-CH_2-CHX-CH_2-\underset{\underset{OCH_3}{|}}{C}(CH_3)-C_6H_5 \qquad R-CH_2-\underset{\underset{CO}{|}}{CH}-CH_2-\underset{\underset{O}{|}}{C}(CH_3)-C_6H_5$$
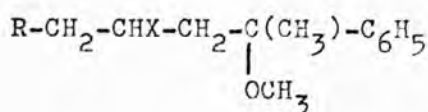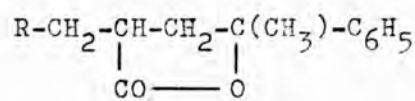
(XIII)   (XIV)

70-80% yield based on radical source, is obtained in the most favourable cases. Since the resonance energies of λ-cyano-, carboxy- and keto- alkyl radicals cannot be as high as that of allylic or benzylic radicals, the observed sequence of reactivity and consequent synthetic possibilities are clearly determined by the nucleophilic character of (XVII) and (XVIII).

The radical source offered interesting prospects of synthetic success for the homolytic alkylation of heteroaromatic bases, in that the reaction medium (Ag^{2+}, $S_2O_3^{2-}$ and SO_4^{2-}) has no specific oxidative action towards the alkyl radicals. In fact the main interaction of alkyl radical R· is not so much of its oxidation, but a hydrogen abstraction from alkanoic acid, with the formation of the compound R-H in high yield[52]. Therefore in the presence of a protonated heteroaromatic base competition would be between addition of the alkyl radical to the base or hydrogen abstraction. But previous results[69,70] indicated that the first reaction was considerably favoured and that, therefore this redox system could be particularly suitable for homolytic alkylation. When heteroaromatic bases have more than one reactive position (α or γ to the heterocylic nitrogen) it is possible to obtain the mono-alkylation product limiting the conversion because the first alkyl group reduces only slightly the reactivity of substrate (Table F)

Table F

Alkylation of Pyridine

R-CO.OH R=	Base: persulphate ratio	Converted Base %	Yield %	Products (%)
CH₃-CH₂-	1:3	100	98	2-Et-(1.5); 4-Et-(21.5); 2,6-diEt-(41.5); 2,4-diEt-(26.5); 2,4,6-triEt-(9)-
CH₃-CH₂-	3:1	-	36	2-Et-(44); 4-Et-(56)-
(CH₃)₂CH-	3:1	-	42	2-(CH₃)₂CH-(37); 4-(CH₃)₂CH-(63)-
(CH₃)₃C-	3:1	-	52	2-t-Bu-(32); 4-t-Bu-(68)-

Synthetic interest arises from the following characteristics

(i) The sources of alkyl radicals are cheap, readily available and very versatile. A number of alkyl radicals can be obtained from the corresponding carboxylic acids.

(ii) Yields are good and the experimental conditions are particularly simple, the reactions can be carried out in aqueous solution at moderate temperatures.

(iii) Electrophilic (Friedel-Crafts) alkylation, which is important in homocyclic series, is not applicable with the heteroaromatic bases and in any case would lead to completely different orientation. Also nucleophilic alkylations with organo-metal reagents (lithium alkyls, Grignard reagents) give good results only in a few cases.

(iv) The substitution occurs without rearrangement even in the case of neopentyl and cyclopropyl radicals and without isomerization of reaction products, in contrast to the corresponding occurs in electrophilic alkylation.

(v) The selectivity of the attack is very high since some positions are much more reactive towards nucleophilic alkyl radicals than others.

The last aspect also allows the introduction of t-alkyl-groups, that could not be introduced by homolytic substitution in homocyclic systems[71]. Also under comparable conditions, higher conversions are obtained with tertiary and secondary than with primary or methyl radicals, owing to greater nucleophilic character of secondary and tertiary radicals, notwithstanding the fact that their reaction is not sterically favoured. The reactions are sensitive to polar influences. Thus for example, 4-cyano-pyridine

is alkylated more readily than pyridine, again because of the
nucleophilic character of the alkyl radicals[72].

The polar properties of the alkyl radicals also displayed
in these reactions are in accordance with the results obtained
from the study of the relative reaction rates of homolytic
methylation of 4-substituted pyridine with t-butyl hydroperoxide
as the source of methyl radicals[73]. The behaviour indicates
that the strong electron-deficient nature of the protonated
heteroaromatic bases causes an enhanced contribution of polar
forms in the transition state: and it well emphasizes the intrinsic
nucleophilic character of the alkyl radicals which is sufficient
to observe to the same extent in other reactions of these radicals.

The low reactivity of electron-rich substrates, such as
1,3-dimethoxy-benzene, towards the alkyl radical indicates that
the reactivity cannot be explained on the basis of a dipolar
character of the alkyl radicals, which would react as nucleophilic
and electrophilic species, depending on the polar nature of the
substrate.

(iii) Formation of Alkoxy Radicals:-

The oxidation of 2-methylpropan-2-ol, hexan-1-ol, 2,3-dimethyl-
butan-2-ol and ethylene glycol in the presence of silver salts
take place via alkoxy-radical intermediates arising from the in-
teraction (42).

$$R\text{-OH} + Ag^{2+} \longrightarrow R\text{-O} \cdot + Ag^{+} + H^{+} \underline{\hspace{1cm}} (42)$$
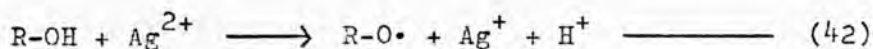
The results obtained by Minisci[74] clearly indicate that
alkoxy-radicals are formed in all cases in the oxidation of the
alcohols with peroxydisulphate and silver salt and this new reaction

may have interesting features. Ag^{2+} is thought to be formed
according to the redox process described in equations (43)
and (44), so that a catalytic amount of silver salt is
effective.

$$S_2O_8^{2-} + Ag^+ \longrightarrow SO_4^{2-} + SO_4^{\cdot-} + Ag^{2+} \quad\text{—— (43)}$$

$$SO_4^{\cdot-} + Ag^+ \longrightarrow SO_4^{2-} + Ag^{2+} \quad\text{——— (44)}$$
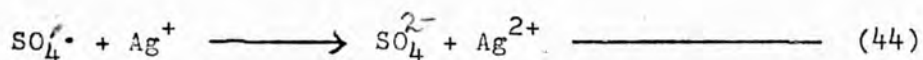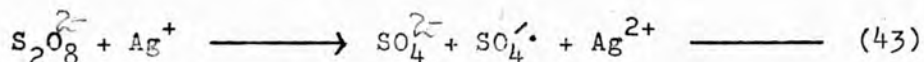
This process may give rise to new interesting selective synthetic
reactions. Thus with t-butyl alcohol the homolytic methylation
of quinoline results from the β-scission of the t-butoxy-
radical (45)

$$(CH_3)_3C-O\cdot \longrightarrow CH_3-CO-CH_3 + \cdot CH_3 \quad\text{——— (45)}$$
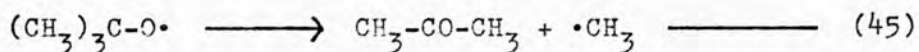
The compounds (XXV) and (XXVI) obtained with $S_2O_8^{2-}$ alone and
with the redox systems $S_2O_8^{2-} | Fe^{2+}$ and $H_2O_2 | Fe^{2+}$ arise by
hydrogen abstraction from t-butyl alcohol (46).
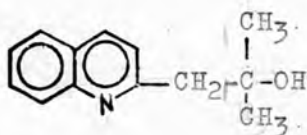
(XXV)
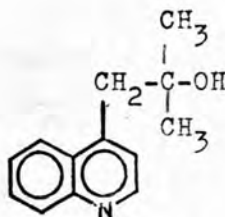
(XXVI)

The abstracting species (R-O$\cdot$) with hydrogen peroxide is $\cdot$OH,
while with $S_2O_8^{2-}$ can be either $SO_4^{\cdot-}$ or $\cdot$OH formed to the well
known equation (47).

$$RO\cdot + CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-OH \longrightarrow ROH + \cdot CH_2-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-OH \quad\text{------ (46)}$$

$$SO_4'\cdot + H_2O \longrightarrow HSO_4 + \cdot OH \quad\text{------------ (47)}$$
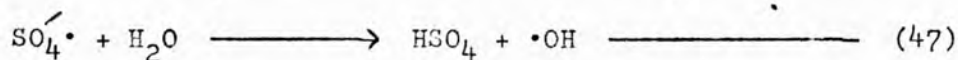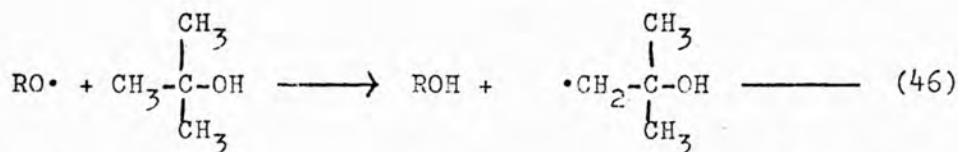
With 2,3-dimethylbutan-2-ol and $S_2O_8{}^{2-} / Ag^+$ the β-scission mainly occurs with the formation of the isopropyl radical (48), but small amount of methyl radical are also formed.

$$\overset{\overset{\displaystyle CH_3}{\diagdown}}{\underset{\underset{\displaystyle CH_3}{\diagup}}{CH}}\text{-}\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}\text{-O}\cdot \quad \begin{array}{l} \nearrow CH_3COCH_3 + CH_3-\overset{\cdot}{C}H-CH_3 \\ \\ \searrow CH_3-\underset{\underset{\displaystyle CH_3}{|}}{CH}-CO-CH_3 + CH_3\cdot \end{array} \quad\text{------ (48)}$$
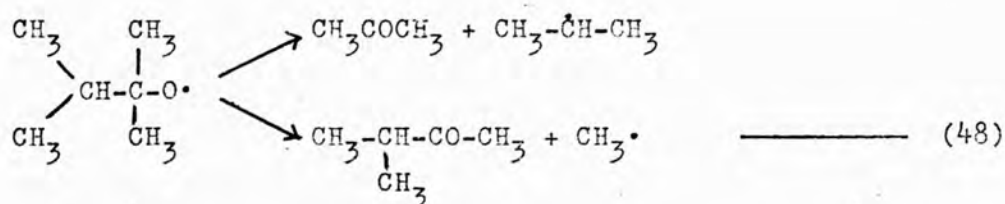
None of the products expected from (48) was observed in the absence of silver salt. The formation of the hydroxymethyl-quinolines (XXVII) and (XXVIII) in the oxidation of ethylene glycol with $S_2O_8{}^{2-} | Ag^+$ also agrees with the radical (49)

(XXVII)   (XXVIII)

$$CH_2OH\text{---}CH_2O\cdot \longrightarrow \cdot CH_2OH + CH_2{=}O \quad\text{------ (49)}$$
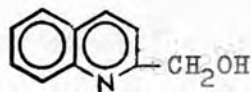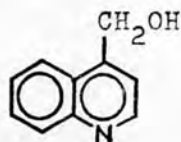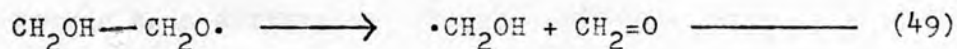
In contrast a hydrogen abstraction (50) occurs in the absence of silver salt and gives the glycol (XXIX) and (XXX); also in this case the abstracting species (RO$\cdot$) can be $SO_4'\cdot$ or $\cdot OH$.

(XXIX)

(XXX)

$$R-O\cdot + CH_2OH-CH_2OH \longrightarrow R-OH + \cdot CHOH-CH_2OH \quad\quad (50)$$
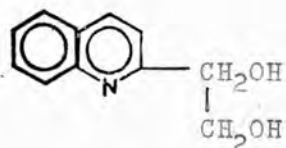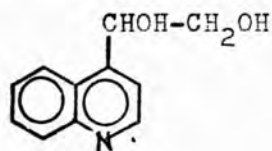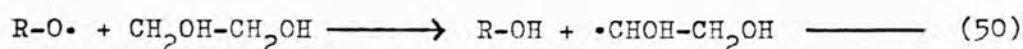
The results obtained in the oxidation of 2-phenyl-ethanol and related compounds supports the following mechanism.

$$Ph-CH_2-CH_2-OH + SO_4^{-}\cdot \longrightarrow Ph-CH_2-CH_2-\overset{+}{\underset{\cdot}{O}}-H + SO_4^{2-}$$

$$Ph-CH_2-CH_2-\overset{+}{\underset{\cdot}{O}}-H \longrightarrow Ph-CH_2-CH_2-O\cdot + H^{+}$$

$$Ph-CH_2-CH_2-O\cdot \longrightarrow Ph-CH_2\cdot + CH_2=O$$

$$2Ph-CH_2\cdot \longrightarrow Ph-CH_2-CH_2-Ph$$
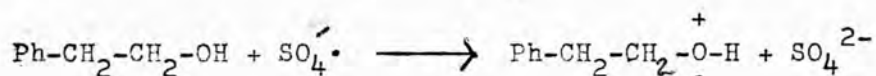
It was also suggested that with primary and secondary alcohols the initial formed alkoxy-radicals rapidly interconverts to its thermodynamically more stable isomer $R_2\overset{\cdot}{C}-OH$, thus explaining the difficulty in establishing alkoxy-radicals as intermediates in alcohol oxidation processes[75]. Norman[76], on the ground of analogous results obtained in the oxidation of phenylacetic acid, has already suggested a different mechanism involving the addition of radical $SO_4^{-}\cdot$ to the aromatic ring according to the following scheme (51).
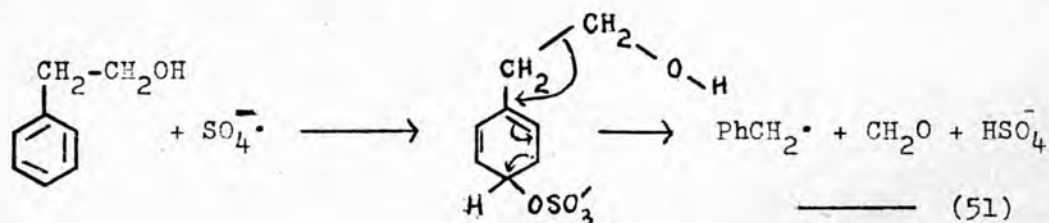
$$\longrightarrow PhCH_2\cdot + CH_2O + HSO_4^{-} \quad\quad (51)$$

The mechanism suggested by Minisci is more reasonable than
that of Ledwith, Russell and Sutcliffe because the ionization
potentials of the alkylbenzenes are somewhat lower than those of
the alcohols (52).

$$
\underset{}{\text{Ph}}\text{CH}_2\text{-CH}_2\text{OH} + \text{SO}_4^{-}\cdot \longrightarrow \text{SO}_4^{2-} + \underset{}{\text{Ph}^{+}}\text{CH}_2\text{-CH}_2\text{OH} \longrightarrow \text{PhCH}_2\cdot
$$

$$
\text{CH}_2\text{O} + \text{H}^{+} \qquad\qquad (52)
$$
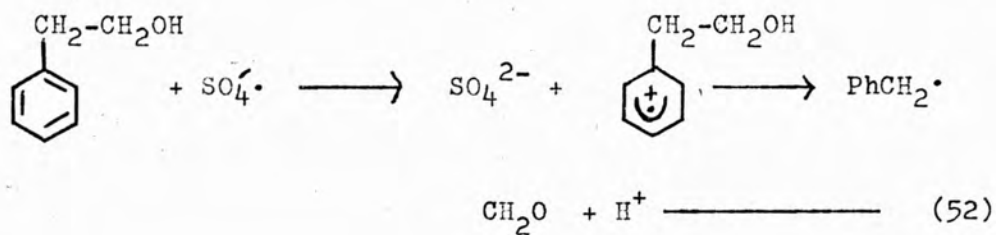
In an analogous way the oxidation of phenylacetic acid could
be explained (53).

$$
\underset{}{\text{Ph}}\text{CH}_2\cdot\text{COOH} + \text{SO}_4^{-}\cdot \longrightarrow \text{SO}_4^{2-} + \underset{}{\text{Ph}^{+}}\text{CH}_2\text{COOH} \longrightarrow \text{PhCH}_2\cdot
$$

$$
\text{CO}_2 + \text{H}^{+} \qquad\qquad (53)
$$
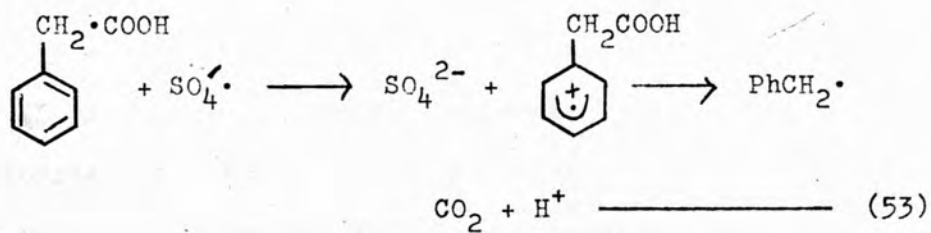
VI) AIMS OF RESEARCH:

In the view of the work discussed in sections II, III, IV(iii), the original aims of research were modified somewhat. Firstly, it was desired that a test should be made on Davies, Hey and Tiecco's prediction[21] (i.e. the production of free radicals in the reactions of Grignard reagents with organic halides in the presence of cobaltous chloride in aromatic solvents) with vinyl bromide and 1-bromocyclohex-1-ene as a source of vinyl radicals. It was also hoped to study the effect of temperature on the yields of these reactions[21]. With the publications of the work of Minisci (which was discussed in section V(ii)), this task became of greater interest, especially with cyclohexene-1-carboxylic acid and acrylic acid as sources of vinyl radicals.

The present dissertation records the reactions of some vinyl radicals with aromatic solvents, produced from cobalt chloride catalyzed reactions of Grignard reagents in the presence of organic halides and from silver catalyzed oxidative decarboxylation of acids.

EXPERIMENTAL

7) REAGENTS:-

Anhydrous Cobaltous(II) Chloride (BDH) was finely powdered and
dried at 160°C for 10-12 hours.

Grignard reagents were prepared from the corresponding halides.
Methylmagnesium iodide was prepared under nitrogen in ether
as described by Kharasch and Reinmuth[77]. Magensium turnings
(0.5 mole, 12 g.) of 99.4% purity were placed in ether (250 ml.)
in a well dried, two necked round bottomed flark under a nitrogen
atmosphere. Methyl iodide (o.25 mole, 35.5 g.) in an equal volume
of sodium-dried ether, was added dropwise to the magensium.
A crystal of iodine was added initially to start the reaction.
After the addition of the alkyl iodide was complete, the mixture
was heated for one hour, to complete the reaction. The solution
of methylmagnesium iodide was filtered through glass wool. Other
Grignard reagents were prepared in a similar way. For preparing
phenylmagnesium bromide, initially the mixture was heated to
start the reaction. In the case of α-naphthylmagnesium bromide,
p-methylphenylmagnesium bromide and p-chlorophenylmagnesium
bromide, initially the mixture was heated for 4-5 hours to
start the reaction.

Solvents. Commercially available materials were used after
drying over anhydrous calcium chloride. Chlorobenzene and
fluorobenzene were redistilled at 132° and 85.2°/760 mm. res-
pectively and dried over anhydrous calcium chloride. Pyridine
was redistilled at 115.5°/760 mm. and dried over solid potassium
hydroxide. Styrene was distilled at 42-43°/18 mm. and dried
over anhydrous calcium chloride. Cumene and toluene were

redistilled at 152-3° and 110.6°/760mm. respectively and were dried over anhydrous magnesium sulphate.

Vinyl bromide (98% pure), vinylnaphthalene (98%), 4-methylstyrene (98%), 4-chlorostyrene (98%) and 1-phenylcyclohexene (98%) were commercially available samples used without further purification.

β-Bromostyrene was prepared from 3-phenyl-2, 3-dibromopropanoic acid[78] (m.p. 200-202°C), itself prepared by dropwise addition of liquid bromine (0.1 mole, 16g) in 1,1,1-trichloroethane (10 ml) to boiling solution of cinnamic acid (0.1 mole, 15g) in 1,1,1-trichloroethane (100 ml). Crystallization of the product from 1,1,1-trichloroethane gave m.p. 200-202°C. 3-phenyl—2, 3-dibromopropanoic acid (29g) on dehydrobromination and decarboxylation with sodium hydroxide in water[79], after refluxing at 78± 3°C gave β-bromostyrene (60%, b.p. 44-54°/0.2-0.8 mm., 98% pure by g.l.c.)

β-Methylstyrene was prepared by dehydration of 1-phenylpropan-1-ol with solid potassium hydroxide. 1-phenylpropan-1-ol[80] was prepared from the reaction of ethylmagnesium bromide (0.25 mole, 33.25g) with benzaldehyde (0.25 mole, 26.50g). The reaction mixture was vigorously stirred and cooled. Almost the whole of crude product was distilled constantly at 131-132°C/50 mm. leaving very little residue. Dehydration with solid potassium hydroxide gave β-Methylstyrene (35.50%, b.p. 176-7°C, 98% pure by g.l.c.)

1-Bromocyclohexene was prepared from 1,2-dibromocyclohexene[81], itself obtained by the addition of bromine (0.22 mole, 35g.) in 25 ml of carbon-tetrachloride to cyclohexene (0.25 mole, 20.50g.) in 50 ml of Carbontetrachloride, keeping the temperature between 0°-3°C. 1,2-Dibromocyclohexene (50g, 108-112°C/25 mm.) on dehydrobromination[82] with boiling quinoline (500 ml) gave 1-bromocyclohexene (10%, 86-86.5°C/20 mm., 97.3% pure by g.l.c.)

1,1'-Bicyclohexenyl. This was prepared[83] from 1,1'-dihydroxy-1,
1'-bicyclohexyl, itself prepared when magnesium turnings (15.50g.)
in benzene (175 ml.) were treated with mercuric chloride (30g.) dis-
solved in dry cyclohexanone (100 g.) under reflux. The product was pur-
ified by recrystallization from high-boiling petroleum ether as white
needles, m.p. 128-129.5°C. The resulting 1,1'-dihydroxy-1, 1'-dicyclo-
hexyl by heating under reflux with 10% sulpuric acid for four hours,
then subjected to steam distillation gave 1,1'-bicyclohexenyl (37.56%,
b.p. 101-102°/ 5.5 mm., 97% pure by g.l.c.)

2,3-Dimethyl-2,3-diphenylbutane was prepared[84] by heating isopropyl-
benzene (100g.) and di-t-butyl peroxide (5 g.) together at 110°C for
72 hours under nitrogen. Removal of solvent through a helix packed
column and crystallization of the residue from methanol gave 2,3-dim-
ethyl-2, 3-diphenylbutane (5g, m.p. 114-115°C.)

Phenyl iodosodibenzoate. This was prepared from iodosobenzene [85]
(19 g.), itself prepared from iodobenzenedichloride by treatment
with anhydrous sodium carbonate and then with sodium hydroxide.
This iodosobenzene was added to a solution of benzoic acid (14 g.)
in chloroform (150 ml.) The mixture was shaken gently until the
iodosobenzene has dissolved and then the solution was   filtered.
Chloroform was distilled off from the filtrate and the solid residue
was thoroughly washed with boiling light petroleum (b.p. 40-60°).
The crude material was recrystallized from chloroform-light petroleum
(b.p. 40-60°C) to yield phenyl iodosodibenzoate[86] (20 g ., m.p. 159°C
lit. m.p. 160°C). [86]

Lead tetrabenzoate . This was prepared [87] from lead tetra- acetate
(50 g.), which was added with shaking to molten benzoic acid (60 g.)
at 130°C. When the addition was complete, the liberated acetic
acid was removed at 40 mm. The dry product (80 g.) after

three crystallisation from dry (P_2O_5) methylene chloride, melted
at 185°C with decomposition. This product contained methylene
chloride which was removed by heating at 100°C for 3 hours at
0.01 mm., to give a pale yellow amorphous powder (m.p. 173-74°C,
lit.[87] m.p. 176°C).

Cyclohexene-1-carboxylic acid was prepared[88] by treating
cyclohexanone (10 g.), with Sodium cyanide (12 g.) in water
(50 ml.) in a ice bath and adding sodium bisulphite (25 g.)
in water (60 ml.) slowly, with vigorous stirring during 0.5 hours.
After stirring for a further four hours, the solution was filtered
and the residue was extracted with ether. The solvent was
removed under reduced pressure. The crude cyanohydrin in pyridine
(25 ml.) and benzene (25 ml.) was treated with phosphorus oxychlo-
ride (30 ml.) and pyridine (30 ml.) and heated under reflux to
give 1-cyanocyclohexene, which on hydrolysis[89] with 90% phosphoric
acid at 130-140°C for 5 hours gave cyclohexene-1-carboxylic
acid (6 g., m.p. 35-36°C, lit,[89] m.p. 38°C).

2- and 4-styrylpyridines were prepared[90] from ⍺- and ɣ-picolines
respectively. ⍺- or ɣ-Picoline (25 g.), benzaldehyde (30 g.)
and concentrated hydrochloric acid (10 ml.) were refluxed on an
oil-bath for six to twelve hours. The unchanged picoline was
distilled off at the same temperature. The residual liquid was
cooled and poured into ice cold water with stirring. The precipi-
tate formed was washed with water (the oil solidified upon cooling
in ice overnight). The product was filtered, washed with water
and dried in air. Purification was effected by repeated re-
crystallization from ethanol. ⍺-Styryl-pyridine [m.p. 90°C,
lit.[90] m.p.91°C, 53% (on the basis of aldehyde), reported 57.5%_7
ɣ-Styrylpyridine [m.p. 125°C, lit.[90] m.p. 127°C, 38% (on the basis

of aldehyde used), reported 40-45% 7.

4-Phenylpyridine. This was prepared[91] from benzenediazonium chloride. The aqueous solution of benzenediazonium chloride (prepared from 15 g. of aniline) was dropped into pyridine (150 ml.) during two hours with stirring at 30°. Nitrogen was freely and continuously evolved and the solution darkened. The reaction was completed by warming on the steam-bath for one hour. Concentrated aqueous sodium-hydroxide was added to the mixture when cold and the pyridine layer was extracted with ether and dried over potassium hydroxide. Distillation under reduced pressure, gave a mixture of phenylpyridines (10 g.), which was collected at 170-190°C / 10-20 min. 4-Phenylpyridine separated as a solid from this distillate on cooling and was recrystallised (6 g., m.p. 77°C, lit.[91] m.p. 78°C).

3-Phenylpyridine was prepared by refluxing a mixture of 3-aminopyridine (9.4 g.), benzene (100 ml.) and amyl nitrite for one hour. 3-Phenylpyridine was distilled out at 269-70°C/749 mm. (4.6 g., 97% pure by g.l.c.) leaving little residue.

2-Phenylpyridine was prepared from phenyl-lithium[92], itself prepared from bromobenzene (0.125 mole, 20 g.) and lithium (2 g.) in ether (50 ml.). To this solution, a mixture of pyridine (0.25 mole, 20 g.) in dry toluene (50 ml.) was added with stirring at 110°C, for 8 hours. It was then cooled to 40°C, 35 ml. of water were added. The toluene layer was dried over potassium hydroxide. The material boiling up to 150°C was removed at atmospheric pressure and the residue distilled in vacuo. After two fractional distillation, the yield of 2-phenylpyridine, b.p. 140°/12 mm. was 11-12 g. (98% pure by g.l.c.).

2-Ethyl-N, N-dimethylaniline was prepared by refluxing 2-ethylaniline with trimethylphosphate[93]. Equimolar amount of 2-ethylaniline and trimethylphosphate was refluxed gently for 3-4 hours, refluxing began smoothly. Separation into two layers occurred in 30 to 90 minutes. To the reaction mixture, sodium hydroxide and water added and the amine was extracted with ether. After drying over sodium hydroxide and removing ether, 2-Ethyl-N, N-dimethylaniline was distilled at atmospheric pressure (219°-221°C/740 mm., 90% yield).

1-(3 Chlorophenyl) cyclohexene, was prepared by treating the Grignard reagent, made from m-chlorobromobenzene (40 g.) and magnesium (6 g.) in ether (100 ml.) with cyclohexanone[94] (25 g.). Then the mixture was distilled with 200 ml. of ether, and refluxed for 3 hours to give a solution of 1-(3 chlorophenyl) cyclohexanol (31 g., b.p. 120-130°C). This was refluxed with concentrated hydrochloric acid (400 ml.) to give 1-(3 chlorophenyl) cyclohexene (20 g., b.p. 125-30°/ 760 mm., 97% pure by g.l.c.).

8) <u>GAS-LIQUID-CHROMATOGRAPHY</u>

(i) For qualitative analysis a Pye 104 Gas-Chromatograph was employed with the following column packings, both on celite (80-100 mesh.).

(A) 10% Apiezon (B) 3% OVI

(ii) Compounds were identified by comparison of retention times with those of authentic samples. Quantitative estimation was made by measuring the difference in the area of the substance upon adding a known weight of the substance to a known weight of the reaction mixture. The total yield of the substance could then be deduced.

9) REACTIONS OF GRIGNARD REAGENTS WITH VINYL BROMIDE IN BENZENE.

In general two methods were used to bring the reagents together.
In the first, the Grignard reagent was added slowly at $25^{\circ}C$ to
a suspension of cobalt(II) chloride, vinyl bromide and benzene
(250 ml.). In the second, cobalt(II) chloride was added slowly
to the suspension of Grignard reagent, vinyl bromide and benzene
(250 ml.). In each case the mixture became black and gases were
evolved. After being left overnight dilute hydrochloric acid (3M.)
was added and the mixture was separated into organic and aqueous
layers. The organic layer was combined with ether (2x50 ml.)
used to wash the apparatus and to extract the aqueous layer. The
combined organic layers were washed with saturated sodium hydrogen
carbonate solution and then with water, and dried over sodium
sulphate. The filtered solution after addition of ether washings
(100 ml.) of separating funnel and the desiccant, was concentrated
to about 30 ml. by fractional distillation and was analysed
by Gas-liquid-chromatography. The results are shown in the
following Table G, the solution was concentrated to about
30 ml. containing benzene and styrene.

Table G

Reactions involving Vinyl bromide in benzene (250 ml.)

Run No.	Grignard reagent (mole)	Vinyl bromide (mole)	Cobaltous Chloride (mole)	Product (mole)
1 (a)	MeMgI (0.05)	0.05	0.005	Styrene (nil)
2 (a)	CH$_2$=CHMgBr (0.05)	0.05	0.005	Styrene (nil)
3 (a)	PhMgBr (0.05)	0.05	0.005	Styrene (0.0023)
4 (b)	PhMgBr (0.05)	0.05	0.005	Styrene (0.005)
5 (b)	PhMgBr (0.025)	0.05	0.005	Styrene (0.0007)
6 (b)	PhMgBr (0.05)	0.025	0.005	Styrene (0.002)
7 (b)	PhMgBr (0.05)	0.05	0.01	Styrene (0.0054)
8 (b)	PhMgBr (0.05)	0.05	0.0025	Styrene (0.0011)
9 (b,c)	PhMgBr (0.05)	0.05	0.005	Styrene (0.0013)
10 (b,d)	PhMgBr (0.05)	0.05	nil	Styrene (0.0056)
11 (b,d)	PhMgBr (0.05)	0.05	0.005	Styrene (0.005)

Run No.	Grignard reagent (mole)	Vinyl bromide (mole)	Cobaltous Chloride (mole)	Product (mole)
12 (b,d,e)	α-C$_{10}$H$_7$MgBr (0.05)	0.05	0.005	Styrene (nil), 1-Naphthylethylene (8×10^{-4})
13 (b,d)	p-MeC$_6$H$_4$MgBr (0.05)	0.05	0.005	Styrene (nil), p-Tolylethylene (1.3×10^{-4})
14 (b,d)	p-ClC$_6$H$_4$MgBr (0.05)	0.05	0.005	Styrene (nil), p-chlorophenyl-ethylene (0.0057)

a) Grignard reagent added to the suspension of cobaltous chloride in vinyl bromide-benzene solution at 25°C.

b) Cobaltous chloride added slowly to a mixture of benzene solution of Grignard reagent and vinyl bromide at 25°C.

c) Addition at 0°C, not at 25°C.

d) Addition made to the boiling mixture of benzene
solution of vinyl bromide and Grignard reagent,
under reflux.

e) Naphthalene (0.0015 mole).

10) REACTION OF GRIGNARD REAGENT WITH β-BROMOSTYRENE IN

    BENZENE

In this reaction, the Grignard reagent (methylmagnesium iodide, 0.05 mole) and β-bromostyrene (0.025 mole) in the benzene solution (50 ml.) was treated with cobalt (II) chloride (0.005 mole) and the mixture was refluxed for 3-4 hours. After cooling the product was hydrolysed and analysed as described in the previous section. Gas-liquid chromatography showed the presence of styrene (4×10^{-4} mole), phenylprop-1-ene (8×10^{-4} mole) and phenylprop-2-ene (0.0013 mole), but no stilbene.

11) THE FORMATION OF CYCLOHEX-1-ENYL RADICALS FROM

1-BROMOCYCLOHEXENE

In these reactions, the Grignard reagent (quantities indicated
in the table) and 1-bromocyclohex-1-ene (0.025 mole) in the
aromatic solvent (50 ml.) were treated with cobalt(II) chloride
(quantities indicated in the table). The mixture was then
heated under reflux for 6-8 hours in a nitrogen atmosphere and
after cooling was hydrolysed and analysed as described in the
previous section. Table H shows the results of a number of
such experiments.

Table H

Reactions involving Cyclohex-1-enyl radicals

Run No.	Grignard reagent (mole)	CoCl$_2$ (mole)	Solvent (50 ml.)	Products (mole)
15(a)	MeMgI (0.05)	0.005	benzene	1-Bromocyclohex-1-ene (0.024) 1-Phenylcyclohex-1-ene (3x10^{-4}) 1,1'-Bicyclohex-1-enyl (9x10^{-5})
16	MeMgI (0.05)	0.005	benzene	1-Phenylcyclohex-1-ene (5x10^{-4}) 1,1'-Bicyclohex-1-enyl (8x10^{-5})
17	MeMgI (0.05)	0.005	Cumene	cyclohexene (3.5x10^{-4}) 2,3-Dimethyl-2,3-diphenylbutane (3x10^{-4}) 1,1'-Bicyclohex-1-enyl (3.6x10^{-4}) o-, m-, and p-, Cyclohex-1-enyl-cumenes (0.0026) (o-, 56.52%, m-,21.7% p-, 21.7%)

Run No.	Grignard reagent (mole)	CoCl$_2$ (mole)	Solvent (50 ml.)	Products (mole)
18(b)	MeMgI (0.05)	0.005	Cumene	Cyclohexene (3.3x10^{-4}) 2,3-Dimethyl-2,3-diphenylbutane (3x10^{-4}) 1,1'-Bicyclohex-1-enyl (3.2x10^{-4}) 1-Bromocyclohex-1-ene (0.002) Cyclohexene-1-carboxylic acid (0.007)
19	PhMgBr (0.05)	0.005	Benzene	1-Phenylcyclohexene (0.0023)
20	PhMgBr (0.05)	0.005	Cumene	Cyclohexene (3.2x10^{-4}) 2,3-Dimethyl-2,3-diphenylbutane (3x10^{-4}) 1-Phenylcyclohexene (0.001) 1,1'-Bicyclohex-1-enyl (1x10^{-4}) o-, m- and p- cyclohex-1-enylcumenes (0.023) (o-,56.52%, m-,21.7%, p-,21.7%)

Run No.	Grignard reagent (mole)	CoCl$_2$ (mole)	Solvent (50 ml.)	Products (mole)
21	MeMgI (0.05)	0.005	Toluene	Cyclohex-1-enyltoluenes (0.025) (o-, 48.4%, m-, 31.7%, p-, 19.8%)
				1,2-Diphenylethane (3x10^{-5})
22	MeMgI (0.05)	0.005	Anisole	Cyclohex-1-enylmethoxybenzenes (0.028) (o-,70%, m-,16%, p-,14%)
23	MeMgI (0.1)	0.005	benzene	1-Phenylcyclohex-1-ene (3x10^{-4})
24	MeMgI (0.05)	0.01	benzene	1-Phenylcyclohexene (6x.0^{-4})
25	MeMgI (0.1)	0.01	benzene	1-Phenylcyclohexene (0.0016)
26	MeMgI (0.1)	0.02	benzene	1-Phenylcyclohexene (0.0014)
27	MeMgI (0.2)	0.02	benzene	1-Phenylcyclohexene (0.002)
28	MeMgI (0.2)	0.04	benzene	1-Phenylcyclohexene (0.002)
29(c)	MeMgI (0.1)	0.02	Pyridine	Cyclohex-1-enylpyridines (α-, 61.5%, β-, 41%, γ-, 56.4%)

Run No.	Grignard reagent (mole)	CoCl$_2$ (mole)	Solvent (50 ml.)	Products (mole)
30	MeMgI (0.1)	0.02	Chlorobenzene	Cyclohex-1-enylchlorobenzenes (0.001) (o-, 50%, m-, 29%, p-, 23%)
31	MeMgI (0.1)	0.02	Fluorobenzene	Cyclohex-1-enylfluorobenzenes (o-, 55%, m-, 32%, p-, 13%)

a) No nitrogen atmosphere, but heating under reflux for 6-8 hours.

c) Gas-liquid-chromctography showed three isomers. As the retention times of these isomers were close to those of phenylpyridines, these three isomers guessed to be α-, β- and γ-cyclohex-1-enylpyridines.

b) After destroying the Grignard reagent with solid carbon dioxide.

12) THE FORMATION OF CYCLOHEXYL RADICALS FROM BROMOCYCLOHEXANE.

In these reactions a mixture of the Grignard reagent (quantities indicated in the Table I) aromatic solvent (50 ml.) and bromocyclohexane (0.025 mole) was treated with cobalt(II) chloride (quantities indicated in the Table I). The mixture was heated under reflux for 6-8 hours in a nitrogen atmosphere, and after cooling was hydrolysed and analysed as described in the previous section. Table I shows the results of these experiments.

Table I

Reactions involving Cyclohexyl radicals

Run No.	Grignard reagent (mole)	CoCl$_2$ (mole)	Solvent	Products (mole)
1	MeMgI (0.05)	0.005	Benzene	Phenylcyclohexane (0.002)
				Bromocyclohexane (0.018)
2	MeMgI (0.05)	0.005	Cumene	Cyclohexane (0.0024)
				Bicyclohexyl (1.3x10^{-4})
				2,3-Dimethyl-2, 3-diphenylbutane (0.0013)
3(a)	MeMgI (0.05)	0.005	Cumene	Cyclohexane (0.002)
				2,3-Dimethyl-2, 3-diphenylbutane (0.001)
				Bicyclohexyl (2.6x10^{-4})
				Bromocyclohexane (0.002)
				Cyclohexanecarboxylic acid (0.008)

Run No.	Grignard reagent (mole)	$CoCl_2$ (mole)	Solvent	Products (mole)
4	MeMgI (0.1)	0.005	Benzene	Phenylcyclohexane (0.0016)
5	MeMgI (0.05)	0.01	Benzene	Phenylcyclohexane (0.003)
6	MeMgI (0.1)	0.01	Benzene	Phenylcyclohexane (0.004)
7	MeMgI (0.1)	0.02	Benzene	Phenylcyclohexane (0.005)
8	MeMgI (0.2)	0.02	Benzene	Phenylcyclohexane (0.0058)
9	MeMgI (0.20)	0.04	Benzene	Phenylcyclohexane (0.0054)
10	MeMgI (0.1)	0.02	Chlorobenzene	Cyclohexylchlorobenzenes (0.00093) (o-, 55%, m-, 33.4%, p-, 11.6%)
11	MeMgI (0.1)	0.02	Fluorobenzene	Cyclohexylfluorobenzenes (0.004) (o-, 53%, m-, 44%, p-, 3%)
12	MeMgI (0.1)	0.02	Pyridine	Cyclohexylpyridines (α-, 40%, β-, 25%, γ-, 34%)

a) Destroying the Grignard reagent with solid carbon dioxide, not with water.

13) FORMATION OF VINYL AND PHENYL RADICALS, BY SILVER CATALYZED

OXIDATIVE DECARBOXYLATION OF ACIDS WITH PEROXYDISULPHATE.

General Procedure:- A solution of potassium peroxydisulphate

(0.1 mole) in water (50 ml.) was added at 70-90°C to a stirred

solution of the substrate (0.1 mole), silver nitrate (0.01 mole)

and carboxylic acid (quantities indicated in the Table J) in

10% aqueous sulphuric acid (0.01 mole). At the end of the

addition, two layers were present and carbon dioxide was being

evolved. After the emission of carbon dioxide ceased, stirring

and heating were continued for 20 minutes. The solution was

poured into ice and ammonia (aqueous), extracted with chloroform,

the organic layer washed with 5% sodium hydroxide and water,

dried over calcium chloride, the solvent removed, and the residue

analysed by gas liquid chromatography. Table J shows the results

of these experiments.

Table J

Reactions involving vinyl and phenyl radicals

Run No.	Source of Radical (mole)	Substrate: Persulphate Ratio	Products (mole)
1	Benzoic acid (0.05)	Pyridine 3:1	Phenylpyridines (0.0023) (α-, 87%, β-, 10%, γ-, 2%=)
2	Benzoic acid (0.05)	benzene 3:1	Biphenyl (0.003)
3	Phenyl iodosodibenzoate (0.05)	Pyridine 3:1	Phenylpyridines (0.00223) (α-, 90%, β-, 8%, γ-, 2%)
4	Lead tetrabenzoate (0.05)	Pyridine 3:1	Phenylpyridines (0.0027) (α-, 89%, β-, 9%, γ-, 2%)
5(a)	Propenoic acid (0.1)	Benzene 3:1	Styrene (5×10^{-4})
6(a)	Propenoic acid (0.1)	Benzene 1:3	Styrene (5×10^{-4})
7(b)	Propenoic acid (0.1)	Pyridine 3:1	Vinylpyridines (α-, β- and γ-)
8	2-Methylprop-2-enoic acid	benzene 3:1	Styrene (9×10^{-4}) Phenylprop-1-ene (7×10^{-5}) Phenylprop-2-ene (8×10^{-5})

Run No.	Source of Radical (mole)	Substrate: Persulphate Ratio	Products (mole)
9	But-2-enoic acid (0.1)	benzene 3:1	Styrene (0.001) Phenylprop-1-ene (2×10^{-5}) Phenylprop-2-ene (8×10^{-5})
10	Cinnamic acid (0.05)	benzene 3:1	Trans-stilbene (0.002)
11	Cinnamic acid (0.05)	Pyridine 3:1	Styrylpyridines (0.002) (α-, 50%, β-, 35%, γ-, 15%)
12	Cyclohexene-1-carboxylic acid (0.05)	benzene 3:1	1-Phenylcyclohex-1-ene (2×10^{-4})
13	Cyclohexanecarboxylic acid (0.05)	benzene 3:1	1-Phenylcyclohexane (8×10^{-4})
14	Acetic acid (0.05)	N-N,dimethyl aniline 3:1	No o-, m-, and p- methyl-N, N-dimethylanilines
15	Propionic acid (0.05)	N-N,dimethyl aniline 3:1	No o-, m-, and p- ethyl-N, N-dimethylanilines

a) There was polymer of propenoic acid (5 g.)

b) As qualitative gas liquid chromatography showed three probable isomers, they can be assumed due to vinylpyridines, as reaction with benzene gave styrene.

DISCUSSION

THE PRODUCTION OF FREE RADICALS IN THE REACTION OF GRIGNARD REAGENTS WITH ORGANIC HALIDES IN THE PRESENCE OF COBALTOUS CHLORIDE.

Many reactions of Grignard reagents with organic halides in the presence of cobalt salts involve the formation of free radicals by removal of halogen from the organic halide. Kharasch and Reinmoth[77], on the basis of numerous investigations conducted by Kharasch and co-workers have proposed a cobalt subhalide (CoX) as an active intermediate.

$$RMgX + CoX_2 \longrightarrow RCoX + MgX_2$$

$$RCoX \longrightarrow R\cdot + CoX$$

$$R'X + CoX \longrightarrow CoX_2 + R\cdot'$$

Wilds and McCormack[12] however proposed active cobalt metal as an alternative to the cobalt subhalide as a intermediate, on the grounds that the reactivity of the mixture was reduced only slightly, when Grignard reagent and cobaltous halide were brought together for several hours before the introduction of alkyl halide. This argues strongly for the presence of an stable intermediate such as finely divided active cobalt (or a stable cobalt subhalide).

$$2RMgX + CoX_2 \longrightarrow CoR_2 + 2MgX_2$$

$$CoR_2 \longrightarrow 2R\cdot + Co$$

$$Co + 2R'X \longrightarrow 2R\cdot + CoX_2$$
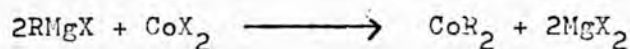
The free radicals thus produced disproportionate, couple, or undergo other reactions. Kharasch and Fields[27] however demonstrated that pyrophoric cobalt metal does not react with bromobenzene, although cobaltous chloride does catalyze the reaction of phenylmagnesium bromide and bromobenzene. Smith[19] and Frey[20] have demonstrated independently that cobalt metal prepared by the reduction of cobaltous chloride with a sodium-naphthalene complex does not react with ethyl bromide. Both of these observation were interpreted as being strong evidence against cobalt metal being the active intermediate. In all cases in which metallic halides was used the reaction is best understood by assuming that they act as electron acceptors. In the course of the reaction they are reduced, in some cases to the metallic state, but the identity of the species which causes coupling between the organic halide and the Grignard reagent is still obscure.

Whatever the mechanism, cobalt catalyzed reactions of Grignard reagents with organic halides are held to produce radicals. These, on dilution of the reaction mixture with aromatic solvents, should attack the solvent to give the products by homolytic substitution. Cobaltous chloride catalyzed reactions of methylmagnesium iodide with vinyl bromide in benzene failed to give styrene. Even the reaction of vinylmagnesium bromide in the presence of cobaltous chloride, vinyl bromide, and benzene failed to give styrene. However the same reaction using phenylmagnesium bromide in the presence of cobaltous chloride, vinyl bromide and benzene afforded styrene. From these observations we postulated

three possibilities

(i)   The reaction occurs through the formation of vinyl radicals.

(ii)   The reaction involves coupling between vinyl bromide and
       Grignard reagent.

(iii) The reaction involves coupling between vinyl bromide and
       Grignard reagent as well as through formation of vinyl
       radicals.

A number of experiments have been carried out using Grignard
reagents derived from 1-bromonaphthalene, p-bromotoluene and
p-chlorobromobenzene. However, cobalt catalyzed reactions of
these Grignard reagents, with vinyl bromide and benzene as a
solvent failed to give styrene, but gave the appropriately
substituted styrenes (1-vinylnaphthalene, p-methylstyrene and
p-chlorostyrene). (Table G) These reactions clearly indicate
coupling between the Grignard reagent and organic halide and
gave no evidence for homolytic substitution by vinyl radicals
of benzene. Further evidence of this mechanism is the reaction
of phenylmagnesium bromide with vinyl bromide and benzene,
which in the absence of cobaltous chloride gives styrene in
the same yield as in the presence of cobaltous chloride. Cobalt
chloride is not essential for the reaction to occur i.e. the
reaction is not through free vinyl radicals, but involves simple
coupling of phenylmagnesium bromide and vinyl bromide.

To prove our mechanism further, the reaction of phenyl-
magnesium bromide in the presence of cobaltous chloride with
vinyl bromide and using chlorobenzene as a solvent, failed to
give chlorostyrene, but styrene only. The same reaction when
carried out using cumene as solvent again failed to give bicumyl
and ethylene, but gave styrene, thus confirming that reaction is

not through vinyl radical formation, but a simple coupling
of phenylmagnesium bromide and vinyl bromide.

In general it can be concluded that the cobalt catalyzed
reaction of phenylmagnesium bromide with vinyl bromide, in the
presence of aromatic solvents proceed in accordance with the
following equation.

$$ArMgBr + CH_2 = CH-Br \longrightarrow Ar-CH = CH_2 + MgBr_2$$

$(Ar = Ph-, \underline{p}-MeC_6H_4-, \underline{p}-ClC_6H_4-, \underline{1}-C_{10}H_7-)$

The effect of the nature of the Grignard reagents and of
a number of other factors, on the yields of styrene derivative
was studied. In the series of runs under similar conditions
involving cobalt catalyzed reactions of phenylmagnesium bromide
with vinyl bromide and benzene, the highest yield of styrene
obtained was 11.20%, based on Grignard reagent. (Table G)

Table G

Reactions involving vinyl bromide in benzene (250 ml.)

Run No.	Grignard reagent (mole)	Vinyl bromide (mole)	Cobaltous Chloride (mole)	Product (mole)	Yield % (based on RMgBr)
1(a)	MeMgI (0.05)	0.05	0.005	Styrene (nil)	
2(a)	CH$_2$=CHMgBr (0.05)	0.05	0.005	Styrene (nil)	
3(a)	PhMgBr (0.05)	0.05	0.005	Styrene(0.0023 mole,	4.64% based on Grignard reagent)
4(b)	PhMgBr (0.05)	0.05	0.005	Styrene(0.005 mole,	10.00% based on Grignard reagent)
5(b)	PhMgBr (0.025)	0.05	0.005	Styrene(0.0007 mole,	2.80% based on Grignard reagent)
6(b)	PhMgBr (0.05)	0.025	0.005	Styrene (0.002 mole,	8% based on Vinyl bromide)
7(b)	PhMgBr (0.05)	0.05	0.01	Styrene(0.0054 mole,	10.80% based on Grignard reagent)
8(b)	PhMgBr (0.05)	0.05	0.0025	Styrene(0.0011 mole,	4.67% based on Grignard reagent)
9(b,c)	PhMgBr (0.05)	0.05	0.005	Styrene(0.0013 mole,	2.60% based on Grignard reagent)
10(b,d)	PhMgBr (0.05)	0.05	Nil	Styrene(0.0056 mole,	11.20% based on Grignard reagent)
11(b,d)	PhMgBr (0.05)	0.05	0.005	Styrene(0.005 mole,	10.00% base on Grignard reagent)
12(b,d,e)	α-C$_{10}$H$_7$MgBr (0.05)	0.05	0.005	Styrene(nil); 1-vinylnaphthalene (8x10^{-4} mole,	1.6% based on Grignard reagent)

Run No.	Grignard reagent (mole)	Vinyl bromide (mole)	Cobaltous Chloride (mole)	Product (mole)	Yield % (based on RMgBr)
13[b,d]	$p\text{-MeC}_6\text{H}_4\text{MgBr}$ (0.05)	0.05	0.005	Styrene (nil),	p-Tolylethylene (1.3×10^{-4}, 0.26% based on Grignard reagent)
14[b,d]	$p\text{-ClC}_6\text{H}_4\text{MgBr}$ (0.05)	0.05	0.005	Styrene (nil),	p-chlorostyrene (0.0057 mole, 11.40% based on Grignard reagent)

a) Grignard reagent was added to the suspension of cobaltous chloride in vinyl bromide-benzene solution at 25°C.

b) Cobaltous chloride added slowly to a mixture of benzene solution of Grignard reagent and vinyl bromide at 25°C.

c) Addition at 0°C.

d) Addition made to the boiling mexture of benzene solution of vinyl bromide and Grignard reagent, under reflux.

e) Naphthalene (0.0015 mole)

On using other Grignard reagents the yields were significantly lower. It has been also found that addition of cobaltous chloride to a mixture of phenylmagnesium bromide, vinyl bromide and benzene resulted in an improvement of the yield of styrene, over that obtained by dropwise addition of a benzene solution of phenylmagnesium bromide to the mixture of cobaltous chloride, vinyl bromide and benzene.

The effect of temperature has also been studied. At $0^{\circ}C$ the yield of styrene decreases significantly from that at $25^{\circ}C$, but the reactions conducted under reflux or with twice the amount of cobaltous chloride, gave the same yield as that at $25^{\circ}C$. The use of an excess of both Grignard reagent and vinyl bromide resulted in an improvement in the yield of styrene. Halving the amount of cobaltous chloride, vinyl bromide, or Grignard reagent in different experiments had no appreciable effect on the yield of styrene.

Substituted vinyl radicals have recently received the attention of many workers, whose interest was focused on the configurational stability of such radicals <u>via</u> a study of hydrogen and halogen abstraction reactions. Attempts to determine the ability of such vinyl radicals to effect homolytic aromatic substitution are now reported.

In order to generate styryl radicals, the cobaltous chloride catalyzed reaction of methylmagnesium iodide with the β-bromostyrene was employed. The reaction was carried out using benzene as diluent, but the reaction failed to give stilbenes, but only styrene, phenylprop-1-ene, and phenylprop-2-ene were produced. In contrast the same reaction applied to 1-bromocyclohex-1-ene, afforded 1-phenylcyclohex-1-ene; g.l.c. also showed

the presence of bicyclohexenyl. The formation of 1-phenyl-cyclohex-1-ene and bicyclohexenyl may be taken as indicative of the intermediacy of 1-cyclohex-1-enyl radicals, according to the following scheme.

$$2MeMgI + CoCl_2 \longrightarrow (Me)_2Co + 2MgClI$$

$$(Me)_2Co \longrightarrow 2Me\cdot + Co$$
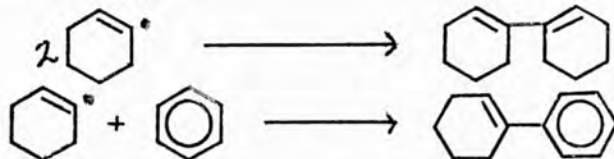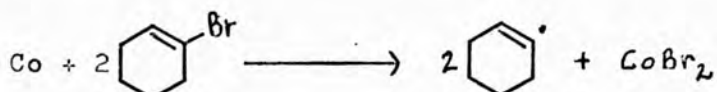
The same reaction with cumene gave cyclohexene and 2,3-dimethyl-2,3-diphenylbutane as the major products. Small amounts of (o-, m-, and p- cyclohex-1-enyl) cumenes were also found.
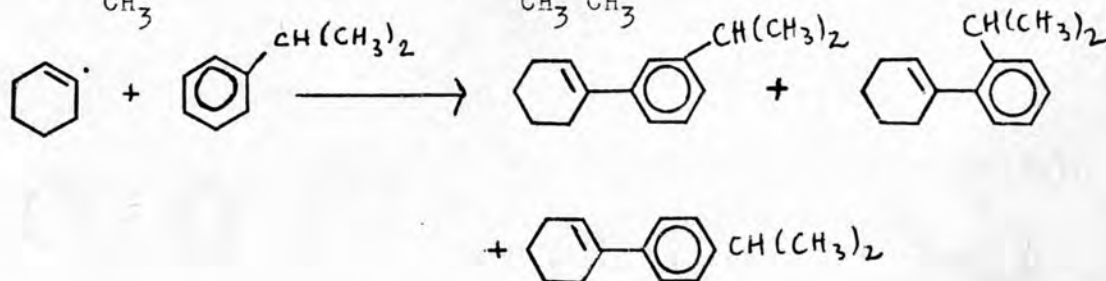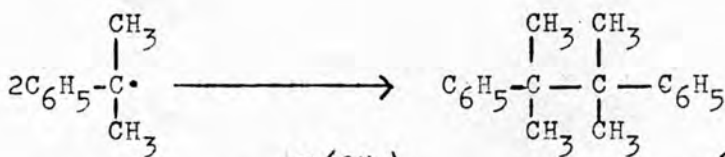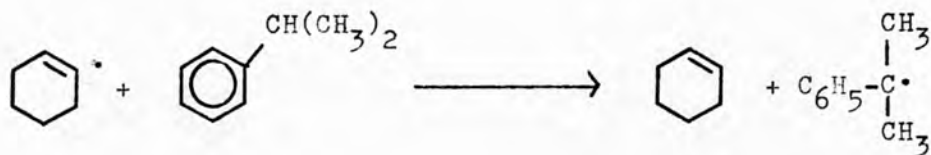
Cobaltous chloride catalyzed reactions of phenylmagnesium-
bromide with 1-bromocyclohex-1-ene in benzene gave 1-phenyl-
cyclohex-1-ene by coupling as well as by radical reactions
because the same reaction with cumene gave cyclohexene, 2,3-
dimethyl-2,3-diphenylbutane and 1-phenylcyclohex-1-ene (coupling
product) as the major products. Gas-liquid chromatography
also showed the presence of small amounts of (o-, m-, and
p- cyclohex-1-enyl) cumenes.

$$2C_6H_5MgBr + CoCl_2 \longrightarrow (C_6H_5)_2Co + 2MgBrCl$$

$$(C_6H_5)_2Co \longrightarrow 2C_6H_5\cdot + Co$$

$$2C_6H_5-\overset{CH_3}{\underset{CH_3}{\overset{|}{\underset{|}{C}}}}\cdot \longrightarrow C_6H_5-\overset{CH_3}{\underset{CH_3}{\overset{|}{\underset{|}{C}}}}-\overset{CH_3}{\underset{CH_3}{\overset{|}{\underset{|}{C}}}}-C_6H_5$$
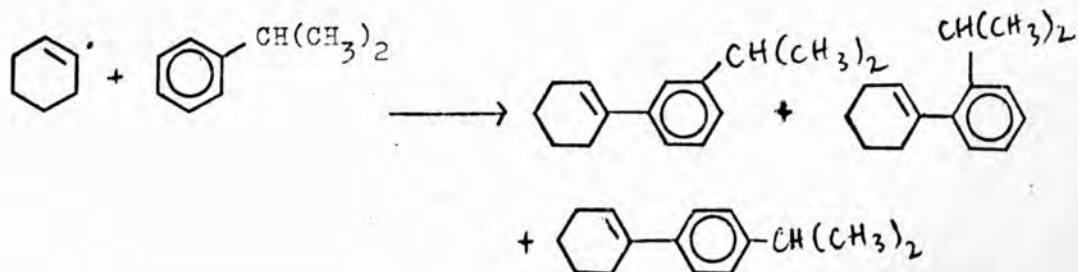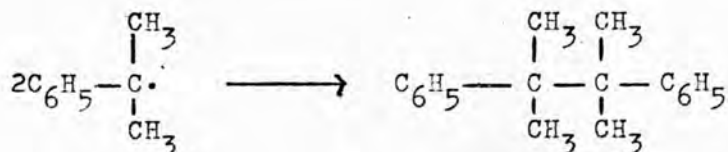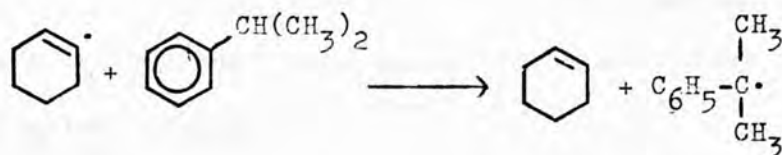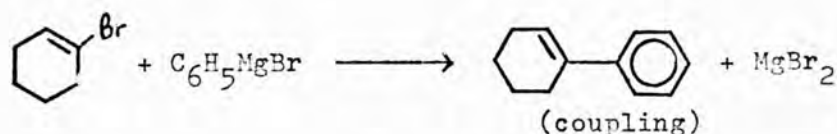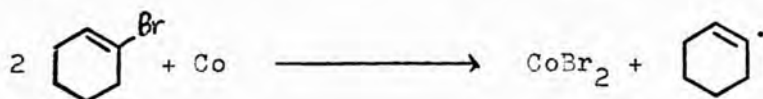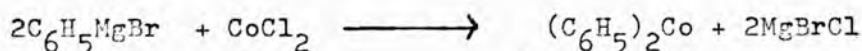
Further evidence for the existence of cyclohex-1-enyl

radicals as intermediates in these reactions is afforded by

the cobalt catalysed reaction of methylmagnesium iodide with

1-bromocyclohex-1-ene and cumene as a solvent, which after

destroying Grignard reagent with solid carbon dioxide gave

cyclohexene, 2,3-dimethyl-2,3-diphenylbutane and cyclohexene-1-

carboxylic acid.   The formation of cyclohexene-1-carboxylic

acid shows that there is the possible interchange of radicals

between 1-bromocyclohex-1-ene and Grignard reagent with the

formation of cyclohex-1-enemagnesium bromide; which on addition

of solid carbondioxide gave cyclohexene-1-carboxylic acid,

according to the following scheme.
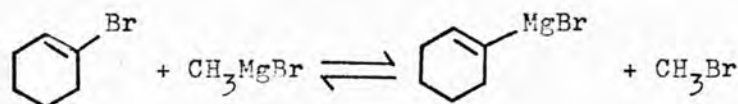
To obtain further evidence for cyclohex-1-enyl radicals,

cobaltous chloride was added slowly to a mixture of methyl-

magnesium iodide, 1-bromocyclohex-1-ene and monosubstituted

benzenes and the isomer ratio from these values were measured

by g.l.c. (Table K)

Table K[42,9]

Isomer ratios in Homolytic Aromatic 1-cyclohex-1-enylation.

Aromatic Solvent	1-Arylcyclohex-1-enes*			1-Arylcyclohex-1-enes[42]			Phenylation[9]		
	o	m	p	o	m	p	o	m	p
$C_6H_5CH_3$	48.4	31.7	19.8	67	— 33 —		67	19	14
$C_6H_5OCH_3$	70	16	14	68	16	16	69	18	13
							79	10	11
C_6H_5Cl	50	29	23				50	32	18
C_6H_5F	55	32	13				54	31	15

*Present work

The values reported may be taken as a clear indication of the homolytic nature of the aromatic substitution, since these values are not very much different from the corresponding values reported for substitution either using another source of cyclohex-1-enyl radicals or using phenyl radicals[42,9]. The data on isomer ratios indicate that no unusual properties can be associated with 1-cyclohex-1-enyl radicals, with regard to homolytic aromatic substitution.

In general the reaction is depicted by the following scheme.

$$2RMgX + CoX_2 \longrightarrow CoR_2 + 2MgX_2$$

$$CoR_2 \longrightarrow 2R\cdot + Co$$

$(\underline{o}\text{-}, \underline{m}\text{-}, \text{ and } \underline{p}\text{-})$
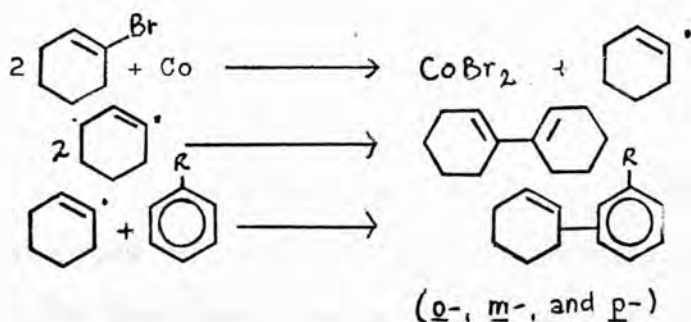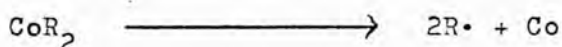
In order to generate cyclohexyl radicals, cobalt catalyzed reaction of methylmagnesium iodide was carried out with cyclohexyl bromide, using benzene as a solvent. The formation of phenylcyclohexane indicated the intermediacy of cyclohexyl radicals. In order to obtain further evidence, cobaltous chloride catalyzed reaction of methylmagnesium iodide with cyclohexyl bromide and with monosubstituted benzenes were studied, and the isomer ratios for these reactions were measured by g.l.c. (Table L).

Table L[9]

Isomer ratios in Homolytic Aromatic Cyclohexylation

| Aromatic Solvent	Cyclohexylation*			Cyclohexylation[9]			Phenylation		
	o	m	p	o	m	p	o	m	p
C_6H_5F	53	44	3	61	35	4	54	31	15
C_6H_5Cl	55	33.4	11.6	54±2	34±2	12±2	50	32	18

*Present work

The values reported may be taken as a clear indication of homolytic nature of the aromatic substitution, since these values are not very different from the corresponding values reported for substitution, using other sources of cyclohexyl radicals and phenyl radicals[9].

So the results given in Table G (p. 86) shows that cobalt catalyzed reactions of Grignard reagents with vinyl bromide in the presence of aromatic solvents result in coupling of Grignard reagent and vinyl bromide but not in substitution by a radical formed from vinyl bromide in the aromatic nucleus. But using 1-bromocyclohex-1-ene and cyclohexyl bromide as halides results in the formation of cyclohex-1-enyl and cyclohexyl radicals.

SILVER (I) CATALYZED OXIDATIVE DECARBOXYLATION OF ACIDS BY PEROXYDISULPHATE.

Silver(I) is involved in an efficient oxidative decarboxylation of acids by peroxydisulphate ion in aqueous solution. The readily available peroxydisulphate ion $S_2O_8^{2-}$ is an excellent and versatile oxidant for a variety of organic and inorganic compounds. The decomposition of the peroxydisulphate ion is however accelerated by strong mineral acids. Alkyl radicals were generated from silver catalyzed oxidative decarboxylation of carboxylic acids by peroxydisulphate according to the reaction

$$RCO_2^- \longrightarrow RCO_2{\cdot} + e$$

$$RCO_2{\cdot} \longrightarrow R{\cdot} + CO_2,$$
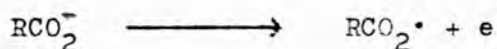
and was recently well discussed by Kochi and coworkers[52]. The catalytic action of silver salt takes place according to the following radical chain.

$$2Ag^+ + S_2O_8^{2-} \longrightarrow 2Ag^{2+} + 2SO_4^{2-}$$

$$RCOOH + Ag^{2+} \longrightarrow R{\cdot} + CO_2 + H^+ + Ag^+$$
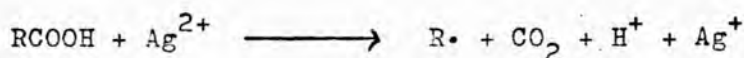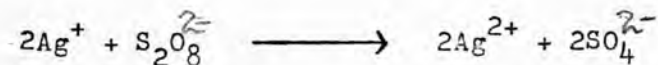
This radical source offered interesting synthetic prospects in the homolytic alkylation of heteroaromatic bases, in that the reaction medium (Ag^{2+}, $S_2O_8^{2-}$) has no specific oxidative action towards radicals. Infact the main reaction of the radicals (R.) is not so much oxidation, but a hydrogen abstraction from the acid with the formation of compounds R-H. Therefore in

the presence of protonated heteroaromatic bases, competition would be between addition of radical to the base or hydrogen abstraction from the parent acid. Minisci's previous results indicated[63,64] that the first reaction was considerably favoured and that therefore, the redox system is particularly suitable for homolytic substitution.

Three potential sources of benzoyloxy radical, and hence of phenyl radical, were treated with peroxydisulphate in the presence of catalytic quantities of silver ion and of pyridine or benzene as substrate. The expected substitution products were obtained, but in poor yields (Table M).

Table M

Reactions involving phenyl radicals.

Run No.	Source of Radical(mole)	Substrate: Persulphate Ratio	Products (mole)
1	Benzoic acid (0.05)	Pyridine 3:1	Phenylpyridines (0.0023) (α-, 87%, β-, 10%, γ-, 2%)
2	Benzoic acid (0.05)	benzene 3:1	Biphenyl (0.003)
3	Phenyliodosodi-benzoate (0.05)	Pyridine 3:1	Phenylpyridines (0.00223) (α-, 90%, β-, 8%, γ-, 2%)
4	Lead tetrabenzoate (0.05)	Pyridine 3:1	Phenylpyridines (0.0027) (α-, 89%, β-, 9%, γ-, 2%)

Hey, Williams and Stirling[86,87] have generated phenyl radicals by the thermal decomposition of lead tetrabenzoate in aromatic solvents. Phenylation by the thermal decomposition of phenyliodosodibenzoate however has been shown to afford an anomalously high yield of benzoic acid. Free benzoic acid can arise from such decompositions in two ways.

(i) By combination of a benzoyloxy radical with a hydrogen atom.

$$Ph\cdot + PhCOO\cdot + ArH \longrightarrow Ph.Ar. \text{ or } PhCO_2Ar + H\cdot$$

$$H\cdot + PhCOO\cdot \longrightarrow PhCOOH$$
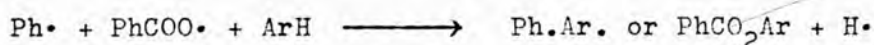
(ii) By the attack of a hydrogen atom on phenyliodosodibenzoate.

$$PhI(OOCPh)_2 + H\cdot \longrightarrow PhI + PhCOO\cdot + PhCOOH$$
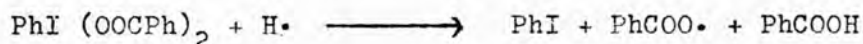
Mechanisms involving the abstraction by benzoyloxy radicals of nuclear hydrogen atoms from aromatic solvent are not tenable, since in the case of nitrobenzene for example, this process would yield an amount of dinitrodiphenyl equivalent to the benzoic acid formed by this mechanism.

$$PhCOO\cdot + ArH \longrightarrow PhCOOH + Ar\cdot$$

$$Ar\cdot + ArH \longrightarrow Ar.Ar + H\cdot$$

No products corresponding to Ar.Ar were found in any of reactions studied by Hey, Williams and Stirling. As silver catalyzed reactions of phenyliodosodibenzoate and lead tetrabenzoate

with pyridine as substrate, gave α-, β- and γ- phenylpyridines
in yields of the same order as that of using benzoic acid,
it is likely that formation of phenylpyridines from phenyl-
iodosodibenzoate and lead tetrabenzoate proceed _via_ benzoic
acid which is decarboxylated to give phenyl radicals. These
can then react with pyridine with the formation of α-, β-
and γ-phenylpyridines, according the following scheme.

$$2Ag^+ + S_2O_8^{2-} \longrightarrow 2Ag^{2+} + 2SO_4^{2-}$$

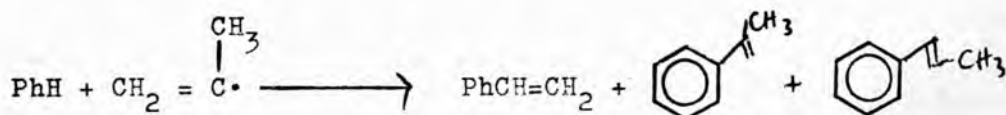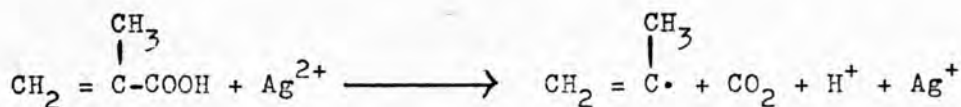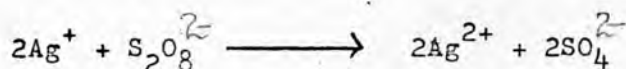$$PhCOOH + Ag^{2+} \longrightarrow Ph\cdot + CO_2 + H^+ + Ag^+$$
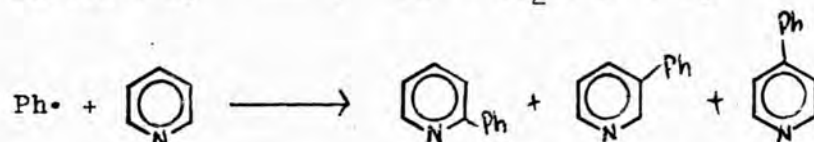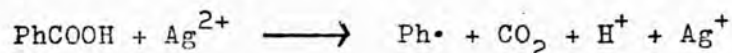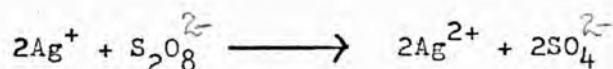
As further evidence of the formation of phenyl radicals, the
silver catalyzed decarboxylation of benzoic acid in the presence
of benzene as a substrate yielded biphenyl.

In order to generate prop-1-en-2-yl and prop-1-en-1-yl
radicals, silver catalyzed reactions of 2 methyl-prop-2-enoic
acid and but-2-enoic acids with benzene as a substrate afforded
in each case a mixture of styrene, phenylprop-1-ene and phenyl-
prop-2-ene, according to the following scheme.

$$2Ag^+ + S_2O_8^{2-} \longrightarrow 2Ag^{2+} + 2SO_4^{2-}$$

$$CH_2 = \overset{CH_3}{\underset{|}{C}}-COOH + Ag^{2+} \longrightarrow CH_2 = \overset{CH_3}{\underset{|}{C}}\cdot + CO_2 + H^+ + Ag^+$$

$$PhH + CH_2 = \overset{CH_3}{\underset{|}{C}}\cdot \longrightarrow PhCH=CH_2 +$$

$$CH_3-CH=CH-COOH + Ag^{2+} \longrightarrow CH_3-CH=CH\cdot + CO_2 + H^+ + Ag^+$$

$$PhH + CH_3-CH=CH\cdot \longrightarrow PhCH=CH_2 +$$
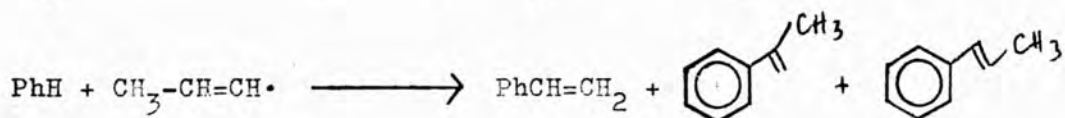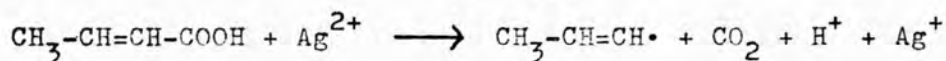
In order to provide styryl radicals, the silver catalyzed reaction of cinnamic acid using benzene as a substrate afforded trans- stilbene.
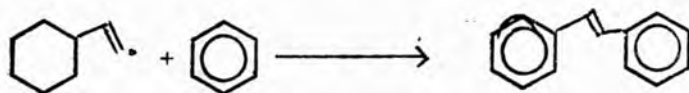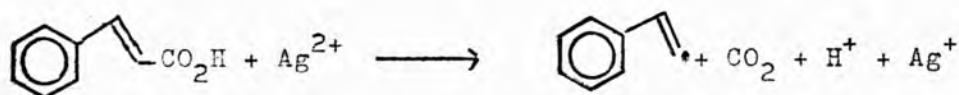
In order to generate vinyl radicals, the silver catalyzed reaction of peroxydisulphate was applied to acrylic acid in the presence of benzene as a substrate. The main product was a polymer of acrylic acid; there was a small yield of styrene.

The same reaction with pyridine and not benzene gave three products which were assumed to be vinylpyridines by analogy with the vinylation of benzene. Similarly, the oxidation of cyclohexene-1-carboxylic acid in the presence of benzene gave 1-phenylcyclohexene (Table N)

Table N

Reactions involving Vinyl radicals.

Run No.	Source of Radical (mole)	Substrate: Persulphate Ratio	Products (mole)
1(a)	Acrylic acid (0.1)	Benzene 3:1	Styrene (5×10^{-4})
2(b)	Acrylic acid (0.1)	Benzene 1:3	Styrene (5×10^{-4})
3(b)	Acrylic acid (0.1)	Pyridine 3:1	Vinylpyridines ($\underline{\alpha}$-, $\underline{\beta}$- and $\underline{\gamma}$-)
4	2 Methylprop-2-enoic acid (0.1)	Benzene 3:1	Styrene (9×10^{-4}), Phenylprop-1-ene (7×10^{-5}), Phenylprop-2-ene (8×10^{-5})
5	But-2-enoic acid (0.1)	Benzene 3:1	Styrene (0.001, Phenylprop-1-ene (2×10^{-5}) Phenylprop-2-ene (8×10^{-5})
6	Cinnamic acid (0.05)	Benzene 3:1	Trans- Stilbene (0.002)

Run No.	Source of Radical (mole)	Substrate: Persulphate Ratio	Products (mole)
7	Cinnamic acid (0.05)	Pyridine 3:1	Styrylpyridines (0.002) ($\underline{\alpha}$-,50%, $\underline{\beta}$-,35%, $\underline{\gamma}$-15%)
8	Cyclohexene-1-carboxylic acid (0.05)	Benzene 3:1	1-Phenylcyclohex-1-ene (2×10^{-4})
9	Cyclohexane carboxylic acid (0.05)	Benzene 3:1	1-Phenylcyclohexane (8×10^{-4})
10	Acetic acid (0.0f)	N-N, dimethyl aniline 3:1	No $\underline{o}$-, $\underline{m}$-, and $\underline{p}$-methyl-N,N-dimethylanilines
11	Propionic acid (0.05)	N-N,dimethyl aniline 3:1	No $\underline{o}$-, $\underline{m}$-, and $\underline{p}$-ethyl-N,N-dimethylanilines

a) The main product was a polymer of acrylic acid (5g.)

b) As qualitative Gas-liquid chromatography showed

three probable isomers, they can be assumed due

to vinylpyridines, as the reaction with benzene   gave styrene.

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