1967

Coupling reactions of radicals with carbanions

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Recommended Citation

Danen, Wayne Cornelius, "Coupling reactions of radicals with carbanions " (1967). *Retrospective Theses and Dissertations*. 3379.
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DANEN, Wayne Cornelius, 1941-
COUPLING REACTIONS OF RADICALS WITH CARBANIONS.

Iowa State University, Ph.D., 1967
Chemistry, organic

University Microfilms, Inc., Ann Arbor, Michigan

COUPLING REACTIONS OF RADICALS WITH CARBANIONS

by

Wayne Cornelius Danen

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Organic Chemistry

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1967

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I. INTRODUCTION

The S_N1 (reaction 1) and S_N2 (reaction 2) are familiar and well documentated mechanisms in which a coupled product is formed in the reaction of a carbanion and organic halogen compound:

$$R'X \xrightarrow{slow} R'^{+} + X^{-} \tag{1}$$

$$R'^{+} + R^{-} \xrightarrow{fast} R'—R$$

$$R^{-} + R'X \longrightarrow [R\cdot\cdot R'\cdot\cdot X]^{-} \longrightarrow R'—R + X^{-} \tag{2}$$

This study is concerned with investigating a new mechanism for such coupling reactions, namely, a free radical chain process in which a key propagation step is the reaction of a radical with a carbanion. This work reports the first authenticated examples of such a reaction.

The initial experiments in this study were conducted in an attempt to observe a somewhat different and simpler process. It was postulated that a coupling reaction could involve an initial electron transfer from the carbanion to the organic halogen compound (reaction 3). This would result in

$$R^{-} + R'X \longrightarrow R\cdot + R'X^{\overline{\cdot}} \tag{3}$$

$$R'X^{\overline{\cdot}} \longrightarrow R'\cdot + X^{-} \tag{4}$$

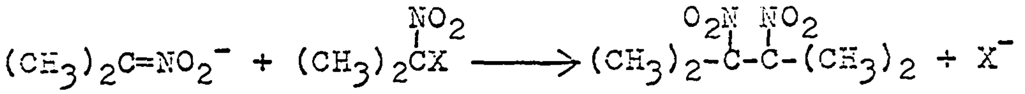
$$R\cdot + R'\cdot \longrightarrow R—R' \tag{5}$$

the formation of a neutral free radical and the radical anion of the organic halogen compound. One would expect the latter to be intrinsically unstable with respect to elimination of halide ion and consequent formation of a new, neutral free radical (reaction 4). The coupled product would then result from the dimerization of the two neutral radicals (reaction 5).

By choosing carbanions that are stable to molecular oxygen it should be possible to distinguish the electron transfer process from a simple S_N2 or S_N1 mechanism since molecular oxygen, being a diradical itself, would intercept and scavenge the free radicals produced in the first two steps of the electron transfer mechanism. One would predict, then, that changing from an inert atmosphere to an oxygen atmosphere would alter the course of the electron transfer reaction drastically, for the radicals formed should be trapped to yield oxidation products rather than coupled products.

By this technique, it was shown that the coupling of acetylacetone, ethyl acetoacetate, and diethyl malonate by base and iodine or bromine does not involve free radicals and presumably occurs by a simple S_N2 displacement. Likewise, the reaction of bromomalononitrile with base to yield pentacyanopropenide ion (1) is not influenced by changing the inert nitrogen atmosphere to one of pure oxygen.

Free radical intermediates were detected in the reaction of the 2-nitro-2-propyl anion with 2-halo-2-nitropropanes (reaction 6). Greater than 90% of the product, 2,3-dimethyl-2,3-dinitrobutane, was formed when the reaction was performed under nitrogen. In the presence of oxygen, coupled product

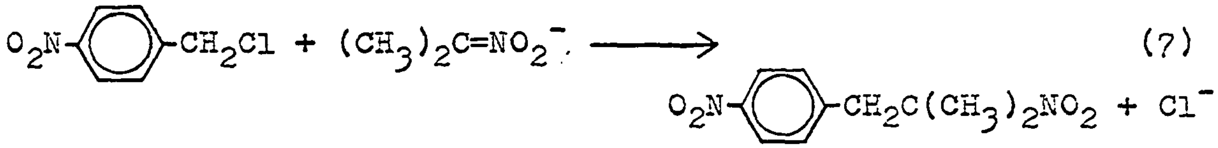


$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}X \longrightarrow (CH_3)_2\text{-}\overset{O_2N}{\overset{|}{C}}\text{-}\overset{NO_2}{\overset{|}{C}}\text{-}(CH_3)_2 + X^- \quad (6)$$

was not formed and the 2-nitro-2-propyl anion was converted to acetone and nitrite ion by a free-radical chain oxidation (2).

However, the simple electron transfer mechanism postulated (reactions 3-5) cannot be operative in this reaction since it was observed that the coupling can be both catalyzed and inhibited. Light caused the reaction to proceed at a much faster rate while small amounts of free radical inhibitors quenched the reaction for extended periods of time. These results clearly demand a free radical chain process.

It was found that the reaction of 2-nitro-2-propyl anion with p-nitrobenzyl chloride (reaction 7) is similar to the



(7)

reaction with the 2-halo-2-nitropropanes in that this reaction can also be catalyzed and inhibited. These results and the fact that m-nitrobenzyl chloride does not give a carbon-alkylated product suggest the following mechanism for the free radical chain process:

Initiation

$$R^- + R'X \xrightarrow{h\nu} R\cdot + R'X^{\overset{\cdot}{-}} \quad (8)$$

Propagation

$$R'X^{\cdot -} \longrightarrow R'\cdot + X^{-} \qquad (9)$$

$$R'\cdot + R^{-} \longrightarrow R'\text{—}R^{\cdot -} \qquad (10)$$

$$R'\text{—}R^{\cdot -} + R'X \rightleftharpoons R'\text{—}R + R'X^{\cdot -} \qquad (11)$$

R^{-} = 2-nitro-2-propyl
R' = 2-nitro-2-propyl or *p*-nitrobenzyl

The initiation step in this process involves the light-catalyzed formation of the radical anion of the halogen compound (reaction 8) which eliminates halide ion to form a neutral radical (reaction 9). This radical then attacks the 2-nitro-2-propyl anion to give the radical anion of the coupled product (reaction 10) which then transfers an electron to another molecule of halogen compound to produce the coupled product and regenerate the chain-carrying species $R'X^{\cdot -}$ (reaction 11).

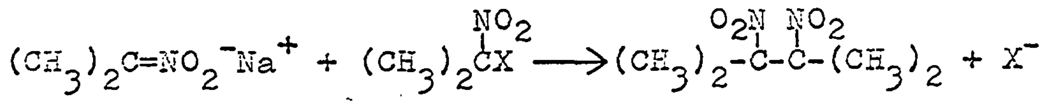
The novel propagation step in the above mechanism involves the hitherto unobserved coupling of a neutral free radical with a carbanion (reaction 10). It will be shown in this thesis that this is the only possible mechanism which explains all details of the reactions considered. Additional experiments were conducted with varying success in an attempt to determine the scope of the newly discovered chain process.

II. LITERATURE AND RESULTS

A. Reaction of 2-Nitro-2-propyl Anion with 2-Halo-2-nitropropanes

1. Literature review

The preparation of 2,3-dimethyl-2,3-dinitrobutane from the reaction of the sodium salt of 2-nitropropane with 2-halo-2-nitropropanes was first reported in 1940 by Seigle and Hass (3), (reaction 12). They found that the percentage



$$(CH_3)_2C{=}NO_2^-Na^+ + (CH_3)_2\overset{NO_2}{\overset{|}{C}}X \longrightarrow (CH_3)_2-\overset{O_2N}{\overset{|}{C}}-\overset{NO_2}{\overset{|}{C}}-(CH_3)_2 + X^- \qquad (12)$$

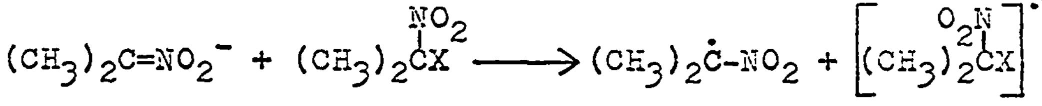
conversion to the dinitro compound was dependent upon the halogen compound used. With the chloride the conversion was approximately 9%, with the bromide 29%, and with the crude iodide 43%. No other products were isolated from the reaction mixture.

A 19% yield of 1-nitro-1-(2-nitroisopropyl)-cyclohexane was obtained when the sodium salt of nitrocyclohexane was allowed to react with 2-bromo-2-nitropropane. No product was obtained when the sodium salt of nitroethane was allowed to react with 1-bromo-1-nitroethane or 2-bromo-2-nitropropane, or when the sodium salt of 1-nitropropane was allowed to react with 1-bromo-1-nitropropane, or when the sodium salt of 2-nitropropane and 1-bromo-1-nitroethane was used. These results seem to indicate that carbon-carbon linkages are not produced when primary nitro compounds are involved. The authors conclude that the reaction tending to form the dinitro compounds is competing with other reactions and the yield of the dinitro compounds depends upon the reaction rates. Also, the formation of the dinitro compounds is determined by the nature of the group or groups attached to the carbon atom holding the nitro group. Although not explicitly stated, these authors imply that the mechanism for formation of the tertiary dinitro compounds by condensation of a halogen derivative of a secondary nitro compound with the sodium salt of a secondary nitro compound (e.g., reaction 12) is simply an S_N2-type displacement process (3, 4). However, if this indeed is their conclusion, it is suprising that the primary nitro compounds fail to react while the sterically more hindered compounds do give the expected products.

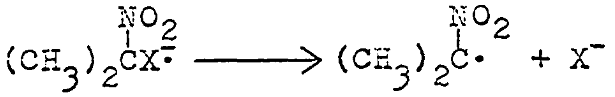
Later work by Hass and Hudgin resulted in a great increase in yield for the reaction of the sodium salt of 2-nitropropane and 2-bromo-2-nitropropane (5); the increase from 29% to 86% was attributed to purer reagents.

2. Results and discussion

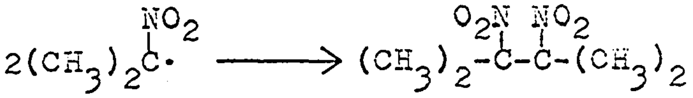
The reaction of the 2-nitro-2-propyl anion with 2-chloro- or 2-bromo-2-nitropropane appeared a likely system to observe an electron transfer-type coupling (reactions 13-15):



$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}X \longrightarrow (CH_3)_2\dot{C}{-}NO_2 + \left[(CH_3)_2\overset{O_2N}{\overset{|}{C}}X\right]^{\dot{-}} \quad (13)$$



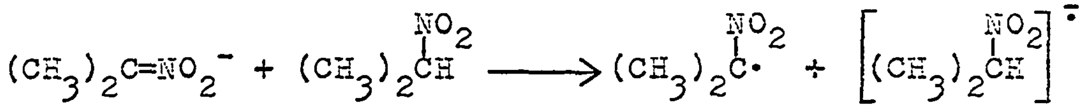
$$(CH_3)_2\overset{NO_2}{\overset{|}{C}}X^{\overline{\cdot}} \longrightarrow (CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot + X^- \qquad (14)$$



$$2(CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot \longrightarrow (CH_3)_2\text{-}\overset{O_2N}{\overset{|}{C}}\text{-}\overset{NO_2}{\overset{|}{C}}\text{-}(CH_3)_2 \qquad (15)$$

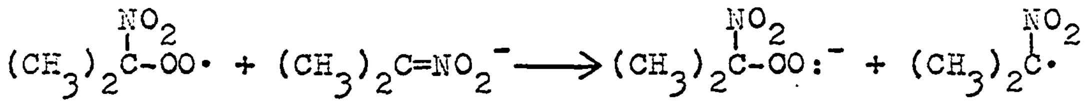
A simple S_N2 displacement of halide by the 2-nitro-2-propyl anion would seem unlikely since this would involve the displacement of a halogen which is attached to a tertiary carbon by a tertiary anion. Such a mechanism would result in a very sterically unfavorable transition state. In addition to steric considerations, the electron transfer process is especially appealing as an explanation for this system because of several other features. First of all, the halogen compound must be sufficiently electronegative to accept an electron in the transfer process. The 2-halo-2-nitropropanes have two groups of high electron affinity, the halogen atom and the nitro group. It has been shown that simple nitroalkanes such as 2-nitropropane can be electrolytically reduced to the radical anion which can be detected by electron spin resonance spectroscopy (6). The addition of a second electron withdrawing group should make an electron transfer process even more feasible. Secondly, the 2-nitro-2-propyl radical formed from the anion by lose of an electron (reaction 13) and from the radical anion of the 2-halo-2-nitropropane (reaction 14) should be quite stable. In addition to being a tertiary radical the unpaired electron can be delocalized over the nitro group. The 2-nitro-2-propyl radical has been postulated as an intermediate in the oxidation of the 2-nitro-2-propyl anion (2).

In the absence of molecular oxygen, yields of greater than 90% of 2,3-dimethyl-2,3-dinitrobutane can be obtained from the reaction of the 2-nitro-2-propyl anion with 2-bromo-2-nitropropane in absolute ethanol. In the presence of oxygen, no detectable amount of dimer is formed. Figure 1 demonstrates that 2-nitropropane does not react readily with oxygen in the presence of a stoichiometric amount or an excess of potassium ethoxide in ethanol solution. However, when 2-bromo-2-nitropropane is added, oxygen is absorbed to the extent of approximately 0.5 mole per mole of 2-nitropropane (Figure 1). Essentially none of the 2-bromo-2-nitropropane is consumed in the oxidation process; the 2-nitro-2-propyl anion is converted to acetone and nitrite ion in yields of 79% and 92% respectively. The oxidation of 2-nitropropane in basic solution has been studied in detail by Russell who showed that the oxidation proceeds via an autocatalytic chain mechanism (2, 7):

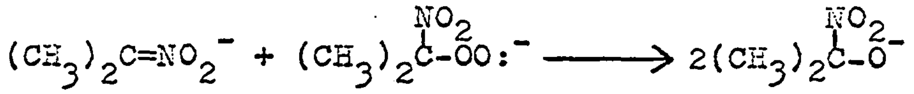


$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}H \longrightarrow (CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot + \left[(CH_3)_2\overset{NO_2}{\overset{|}{C}}H\right]^{\cdot -} \qquad (16)$$

$$(CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot + O_2 \longrightarrow (CH_3)_2\overset{NO_2}{\overset{|}{C}}{-}OO\cdot \qquad (17)$$



$$(CH_3)_2\overset{NO_2}{\overset{|}{C}}{-}OO\cdot + (CH_3)_2C{=}NO_2^- \longrightarrow (CH_3)_2\overset{NO_2}{\overset{|}{C}}{-}OO{:}^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot \qquad (18)$$

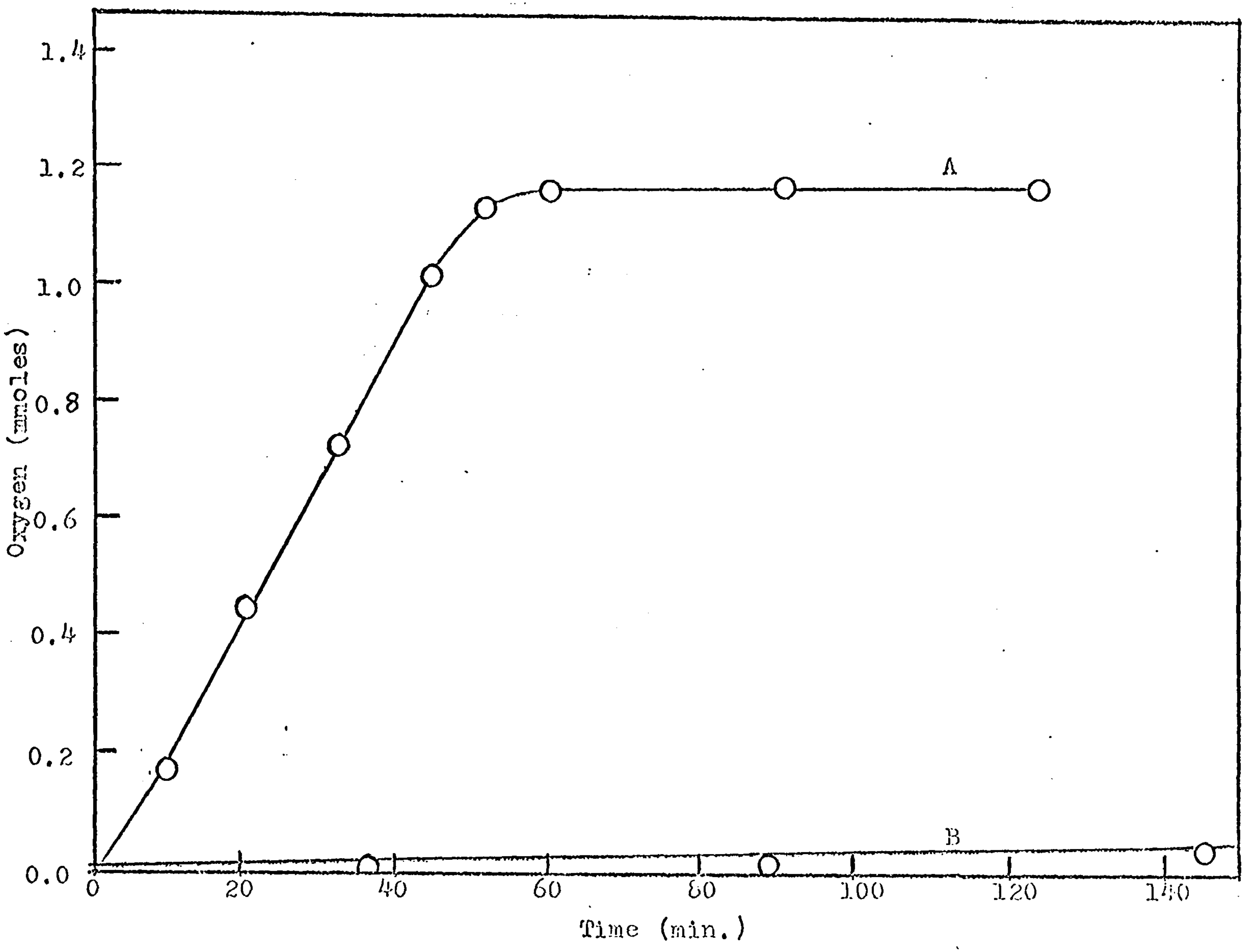


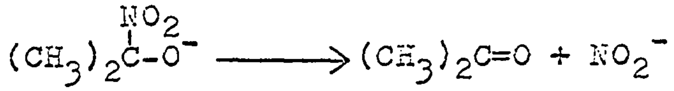
$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}{-}OO{:}^- \longrightarrow 2(CH_3)_2\overset{NO_2}{\overset{|}{C}}{-}O^- \qquad (19)$$

Figure 1. Reaction of 0.256 M (2.56 mmoles) potassium salt of 2-nitropropane and 0.256 M (2.56 mmoles) 2-bromo-2-nitropropane with oxygen in ethanol at ca. 30°C

A. Dark

B. In room light but no 2-bromo-2-nitropropane present


A
B
Oxygen (mmoles)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
20
40
60
80
100
120
140
Time (min.)

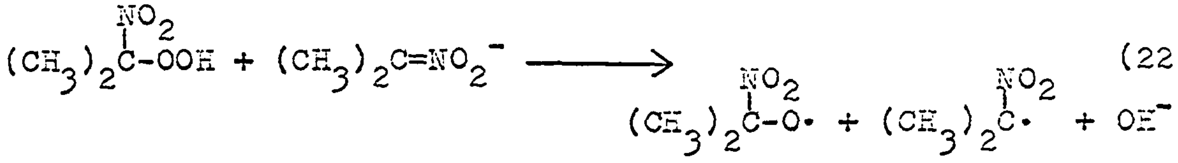


$$(CH_3)_2\overset{NO_2}{\overset{|}{C}}-O^- \longrightarrow (CH_3)_2C{=}O + NO_2^- \tag{20}$$

Overall reaction

$$(CH_3)_2C{=}NO_2^- + \tfrac{1}{2}O_2 \longrightarrow (CH_3)_2CO + NO_2^- \tag{21}$$

The autocatalysis is explained in terms of a hydroperoxide mechanism (equation 22):



$$(CH_3)_2\overset{NO_2}{\overset{|}{C}}-OOH + (CH_3)_2C{=}NO_2^- \longrightarrow (CH_3)_2\overset{NO_2}{\overset{|}{C}}-O\cdot + (CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot + OH^- \tag{22}$$

The amount of oxygen consumed and the yields of acetone and nitrite ion produced in the reaction of the 2-nitro-2-propyl anion with 2-bromo-2-nitropropane in the presence of oxygen are in accord with the observation that only the anion reacts with oxygen. The 2-bromo-2-nitropropane behaves as a catalyst for the oxidation of the anion. This is illustrated in Figures 2-4 where it can be seen that the rate of oxygen absorption depends critically upon the concentration of 2-bromo-2-nitropropane and to a much lesser extent upon the concentration of 2-nitro-2-propyl anion. Figures 3 and 4 show that the total amount of oxygen reacted is independent of the amount of 2-bromo-2-nitropropane present. However, the rate of oxygen uptake depends on the concentration of bromo compound. The catalytic behavior of the 2-bromo-2-nitropropane probably results from its ability to accept an electron

Figure 2. Reaction of Triton B salt of 2-nitropropane and 2-bromo-2-nitropropane with oxygen in ethanol and room light at ca. 30°C

A. 0.507 M (10.14 mmoles) salt of 2-nitropropane
0.507 M (10.14 mmoles) 2-bromo-2-nitropropane

B. 0.254 M (5.07 mmoles) salt of 2-nitropropane
0.507 M (10.14 mmoles) 2-bromo-2-nitropropane

C. 0.507 M (10.14 mmoles) salt of 2-nitropropane
0.254 M (5.07 mmoles) 2-bromo-2-nitropropane

D. 0.254 M (5.07 mmoles) salt of 2-nitropropane
0.254 M (5.07 mmoles) 2-bromo-2-nitropropane

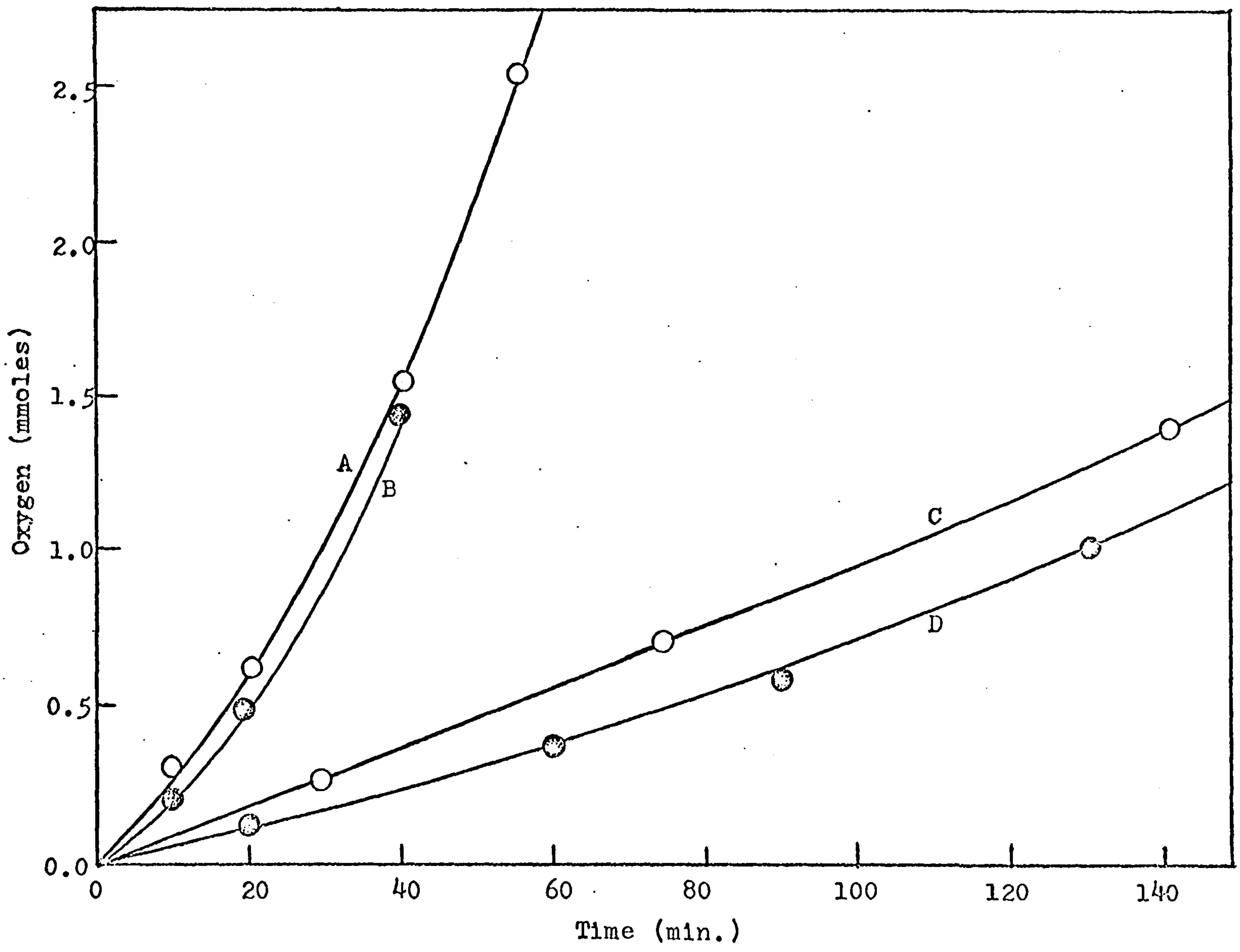

Oxygen (mmoles)
2.5
2.0
1.5
1.0
0.5
0.0
A
B
C
D
0
20
40
60
80
100
120
140
Time (min.)

Figure 3. Reaction of 0.513 M (10.26 mmoles) potassium salt of 2-nitropropane and various amounts of 2-bromo-2-nitropropane with oxygen in ethanol and room light at ca. 30° C

A. 0.513 M (10.26 mmoles) 2-bromo-2-nitropropane

B. 0.256 M (5.13 mmoles) 2-bromo-2-nitropropane

C. 0.128 M (2.56 mmoles) 2-bromo-2-nitropropane

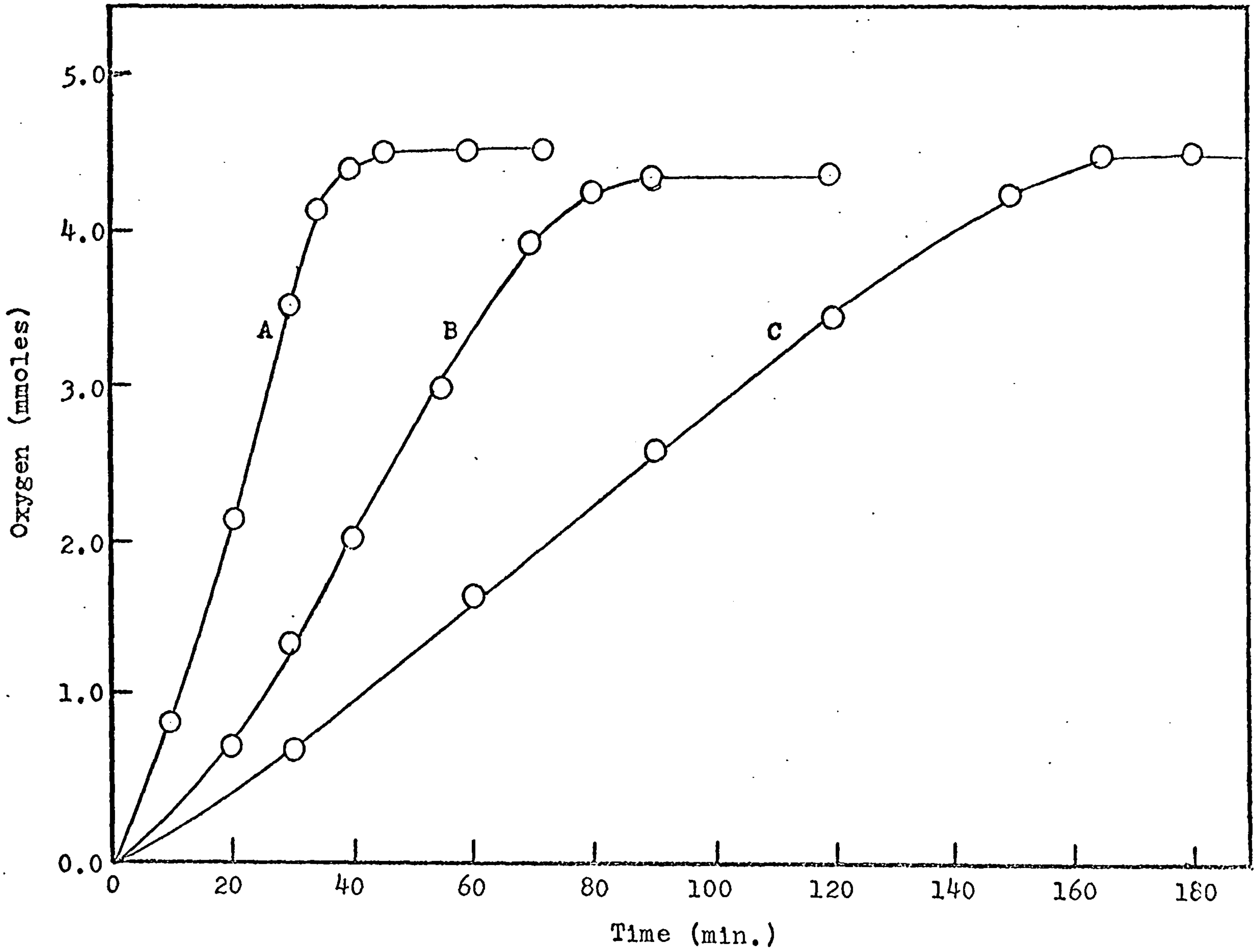
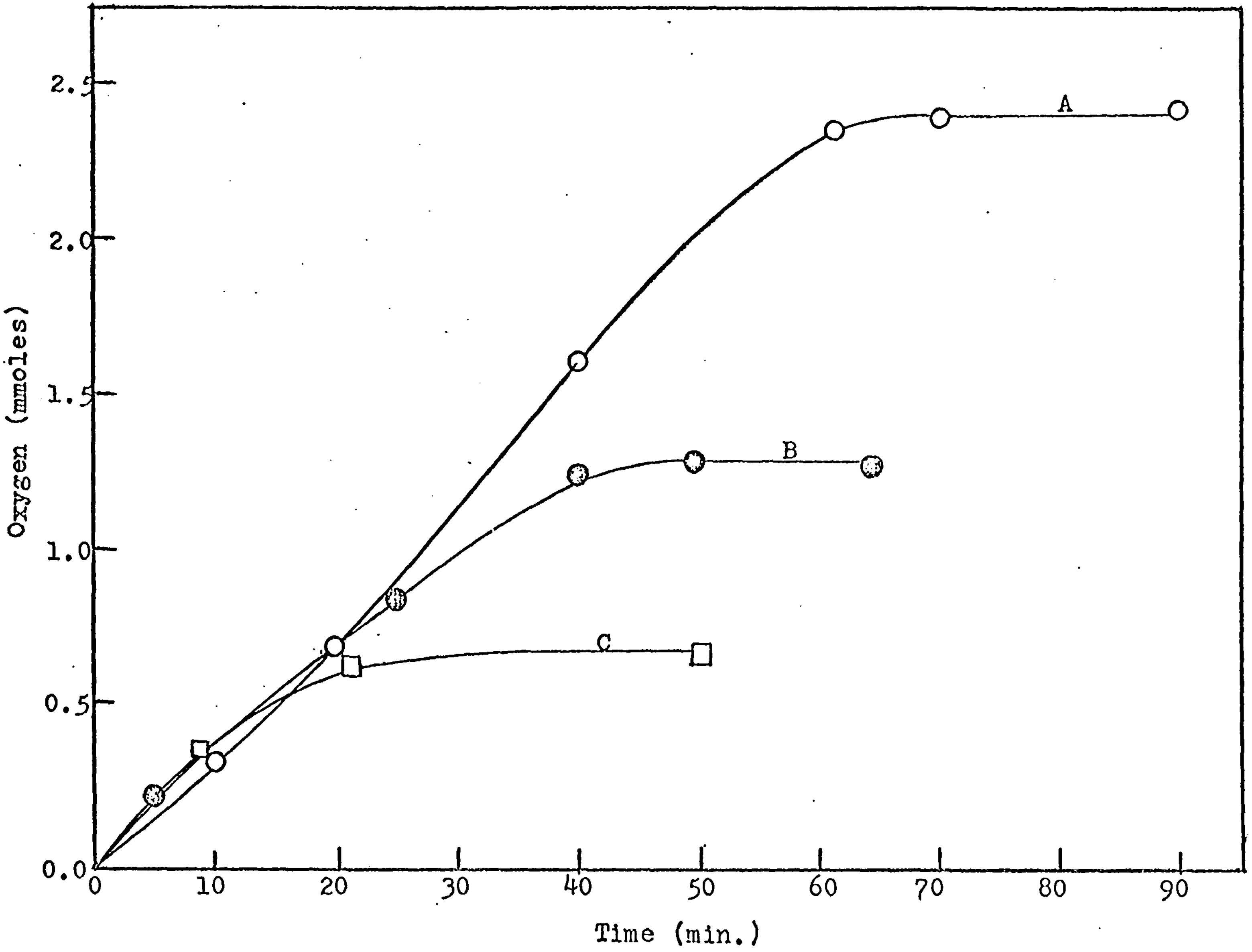

Oxygen (mmoles)
5.0
4.0
3.0
2.0
1.0
0.0
A
B
C
0
20
40
60
80
100
120
140
160
180
Time (min.)

Figure 4. Reaction of 0.256 M (5.12 mmoles) 2-bromo-2-nitropropane and various amounts of potassium salt of 2-nitropropane with oxygen in ethanol and room light at ca. 30°C

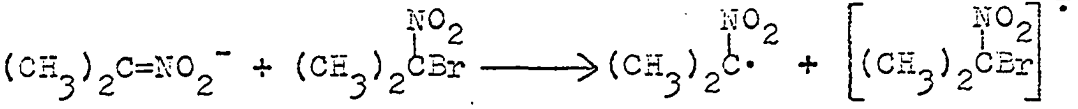
A. 0.256 M (5.12 mmoles) potassium salt of 2-nitropropane

B. 0.128 M (2.56 mmoles) potassium salt of 2-nitropropane

C. 0.064 M (1.28 mmoles) potassium salt of 2-nitropropane


Oxygen (mmoles)
0.0
0.5
1.0
1.5
2.0
2.5
Time (min.)
0
10
20
30
40
50
60
70
80
90
A
B
C

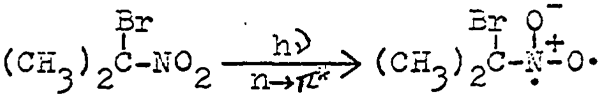
from the anion in an electron transfer process (reaction 23):



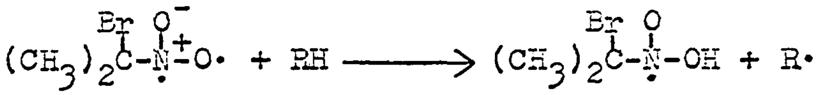
$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}Br \longrightarrow (CH_3)_2\overset{NO_2}{\overset{|}{C}}\cdot + \left[(CH_3)_2\overset{NO_2}{\overset{|}{C}}Br\right]^{\dot{-}} \tag{23}$$

This is analogous to the initiation step proposed for the oxidation of the 2-nitro-2-propyl anion in a deficiency of base (reaction 16). Another possible explanation for the catalysis is the initial decomposition of the 2-bromo-2-nitropropane in the presence of light which has a marked catalytic effect on both the coupling reaction and the oxidation (<u>vide infra</u>).

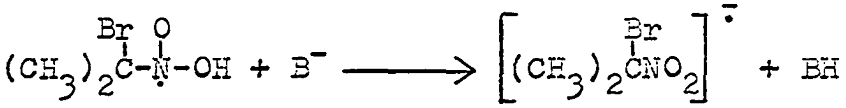
A plausible explanation for the light catalysis is as follows:



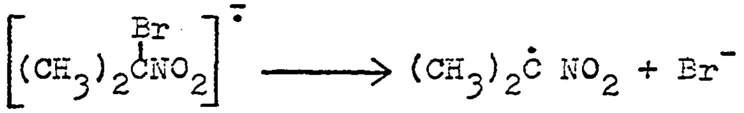
$$(CH_3)_2\overset{Br}{\overset{|}{C}}{-}NO_2 \xrightarrow[n\rightarrow\pi^*]{h\nu} (CH_3)_2\overset{Br}{\overset{|}{C}}{-}\overset{O^-}{\overset{|}{\underset{\cdot}{N}}}\overset{+}{-}O\cdot \tag{24}$$



$$(CH_3)_2\overset{Br}{\overset{|}{C}}{-}\overset{O^-}{\overset{|}{\underset{\cdot}{N}}}\overset{+}{-}O\cdot + RH \longrightarrow (CH_3)_2\overset{Br}{\overset{|}{C}}{-}\overset{O}{\overset{|}{\underset{\cdot}{N}}}{-}OH + R\cdot \tag{25}$$

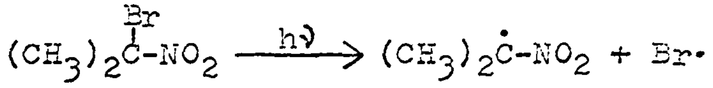


$$(CH_3)_2\overset{Br}{\overset{|}{C}}{-}\overset{O}{\overset{|}{\underset{\cdot}{N}}}{-}OH + B^- \longrightarrow \left[(CH_3)_2\overset{Br}{\overset{|}{C}}NO_2\right]^{\dot{-}} + BH \tag{26}$$

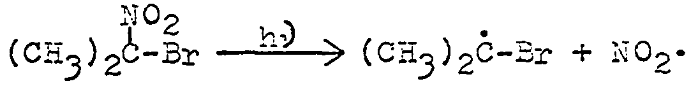


$$\left[(CH_3)_2\overset{Br}{\overset{|}{C}}NO_2\right]^{\dot{-}} \longrightarrow (CH_3)_2\dot{C}\ NO_2 + Br^- \tag{27}$$

Upon irradiation the 2-bromo-2-nitropropane undergoes an n→π* excitation (reaction 24). The excited molecule then abstracts a hydrogen atom from a suitable donor, probably a solvent molecule (reaction 25). This hydrogen is then removed as a proton by a molecule of base to yield the radical anion of the 2-bromo-2-nitropropane (reaction 26) which eliminates bromide ion forming the 2-nitro-2-propyl radical (reaction 27). There is substantial evidence for a process such as this occurring in cases where the nitro group is attached to an aromatic ring (8-10). However, similar examples have not been reported for an aliphatic nitro compound. Instead, photodecomposition occurs in a more straight forward manner (11):

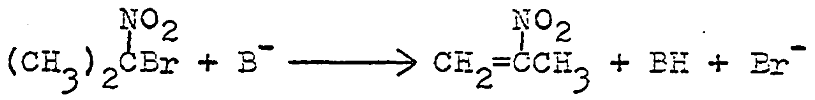


$$(CH_3)_2\overset{Br}{C}\text{-}NO_2 \xrightarrow{h\nu} (CH_3)_2\dot{C}\text{-}NO_2 + Br\cdot \qquad (28)$$



$$(CH_3)_2\overset{NO_2}{C}\text{-}Br \xrightarrow{h\nu} (CH_3)_2\dot{C}\text{-}Br + NO_2\cdot \qquad (29)$$

However, it is noteworthy to mention that the irradiation experiments described in this work were performed in Pyrex glassware which effectively absorbs light of wavelengths less than 2900 Å while reactions 28 and 29 have been reported as occurring at 2537 Å. Another possibility is that the 2-bromo-2-nitropropane undergoes a base-catalyzed elimination of hydrogen bromide to give a nitroolefin:



$$(CH_3)_2\overset{NO_2}{C}Br + B^- \longrightarrow CH_2{=}\overset{NO_2}{C}CH_3 + BH + Br^- \qquad (30)$$

The nitroolefin would be expected to participate in an electron transfer or other process more readily than the bromo compound (reaction 23).

The initial studies on the rate of oxygen uptake in the reaction of the 2-halo-2-nitropropanes with the

2-nitro-2-propyl anion were conducted in room light and quite reproducible rates were observed. However, it was found that irradiation of the reaction solution with a sunlamp resulted in an accelerated rate of oxygen absorption for both 2-bromo-2-nitropropane (Figure 5) and 2-chloro-2-nitropropane (Figure 6). Conducting the reaction in a darkened flask retarded the rate of oxygen uptake but did not completely stop it. No conclusions of a quantitative nature can be inferred from these studies of oxygen uptake because of the autocatlytic nature of the oxidation of the 2-nitro-2-propyl anion (reactions 16-22). However, it can be deduced that free radicals are indeed produced as intermediates which are trapped by oxygen and that light has a catalytic effect on the rate of the oxidation process.

Information more pertinent to the coupling process can be obtained by studying the reaction of the 2-nitro-2-propyl anion with 2-chloro- and 2-bromo-2-nitropropane under an inert atmosphere of nitrogen. Figure 7 reveals that no coupling reaction occurs in the dark for 2-chloro-2-nitropropane for extended periods of time, but a quite rapid decrease in the concentration of the chloro compound occurs when the reaction solution is irradiated. This decrease in concentration of chloro compound is accompanied by a corresponding increase in the amount of coupled product formed (Figure 8). A similar increase in the rate of disappearance of 2-bromo-2-nitropropane is observed when the reaction is conducted in light

Figure 5. Effect of light on the reaction of 0.256 M (2.56 mmoles) potassium salt of 2-nitropropane and 0.256 M (2.56 mmoles) 2-bromo-2-nitropropane with oxygen in ethanol at ca. 30°C

A. Dark

B. Illuminated

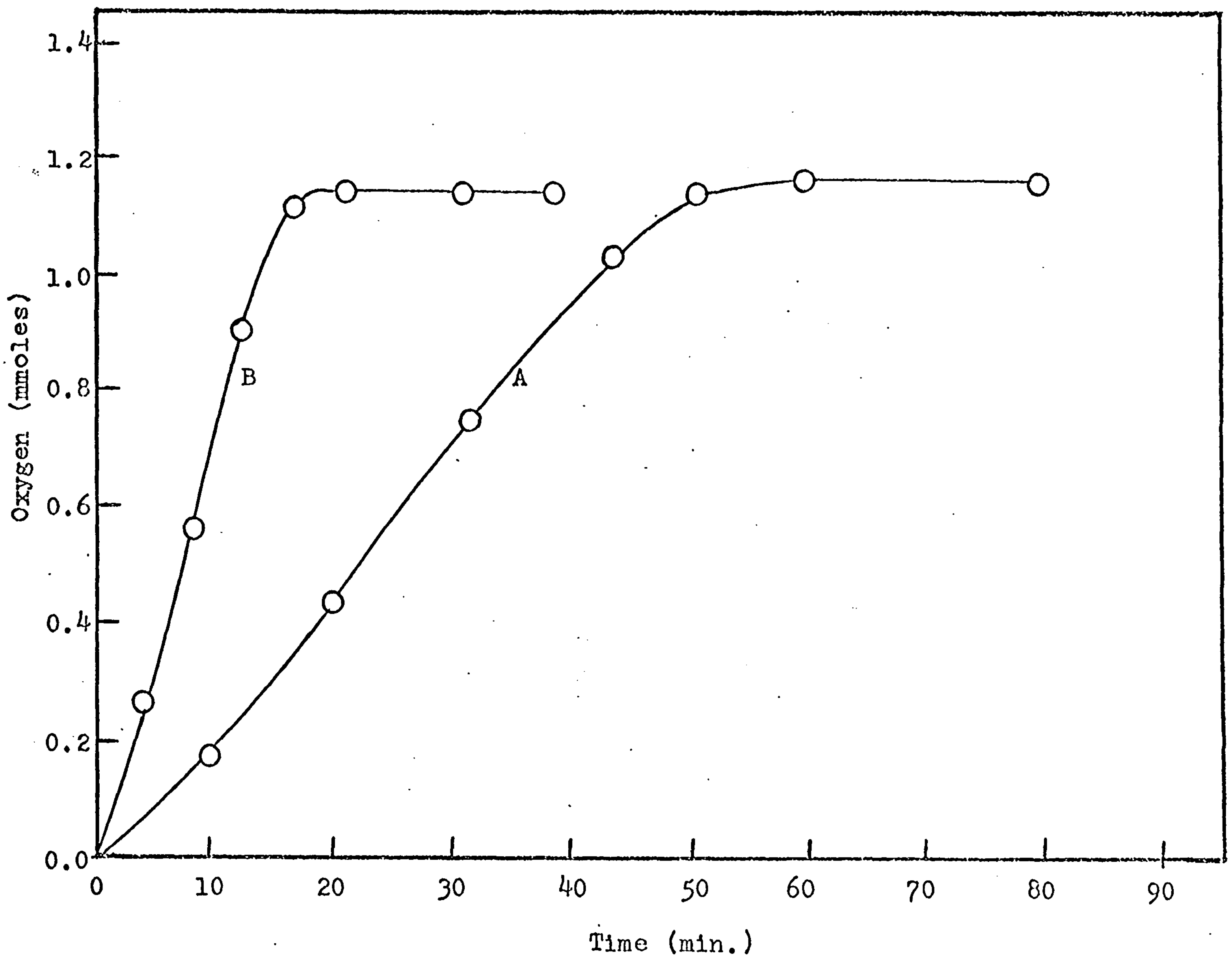

Oxygen (mmoles)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (min.)
0
10
20
30
40
50
60
70
80
90
A
B

Figure 6. Effect of light on the reaction of 0.256 M (2.56 mmoles) potassium salt of 2-nitropropane and 0.256 M (2.56 mmoles) 2-chloro-2-nitropropane with oxygen in ethanol at ca. 30° C

A. Dark

B. Illuminated

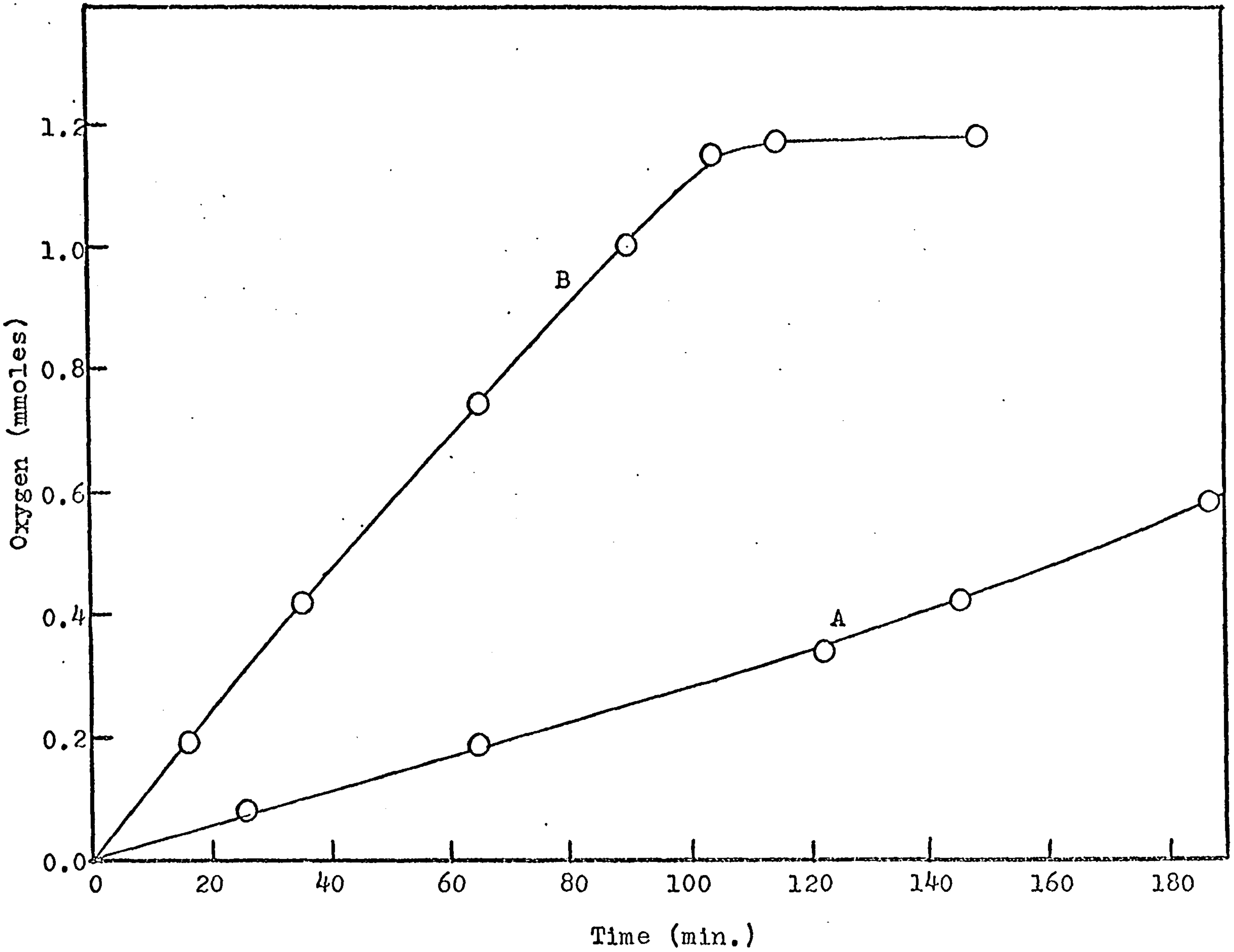

Oxygen (mmoles)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
140
160
180
Time (min.)
B
A

Figure 7. Effect of light on the reaction of 0.256 M potassium salt of 2-nitropropane with 2-chloro-2-nitropropane under nitrogen in ethanol at 30°C

A. Dark

B. Illuminated

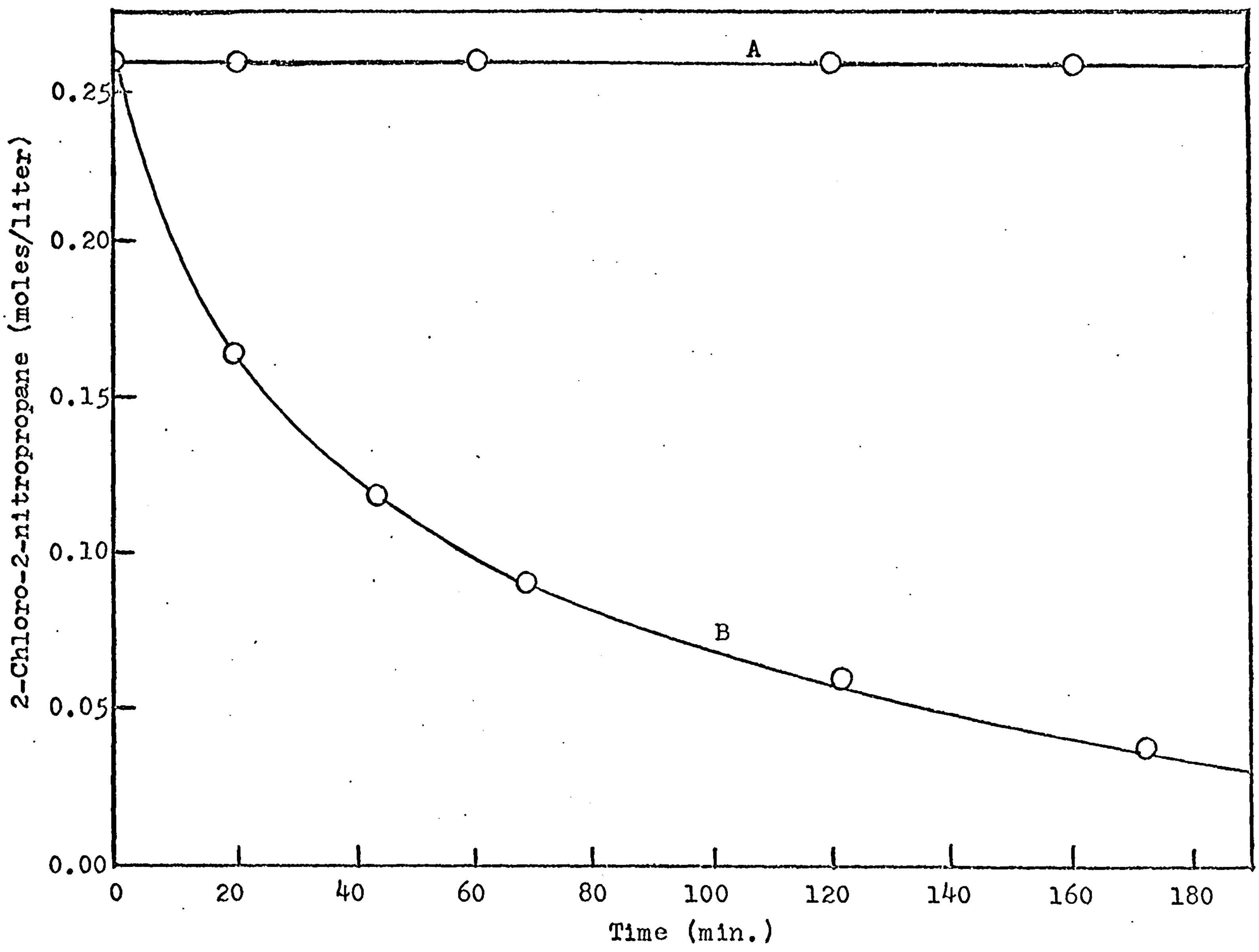
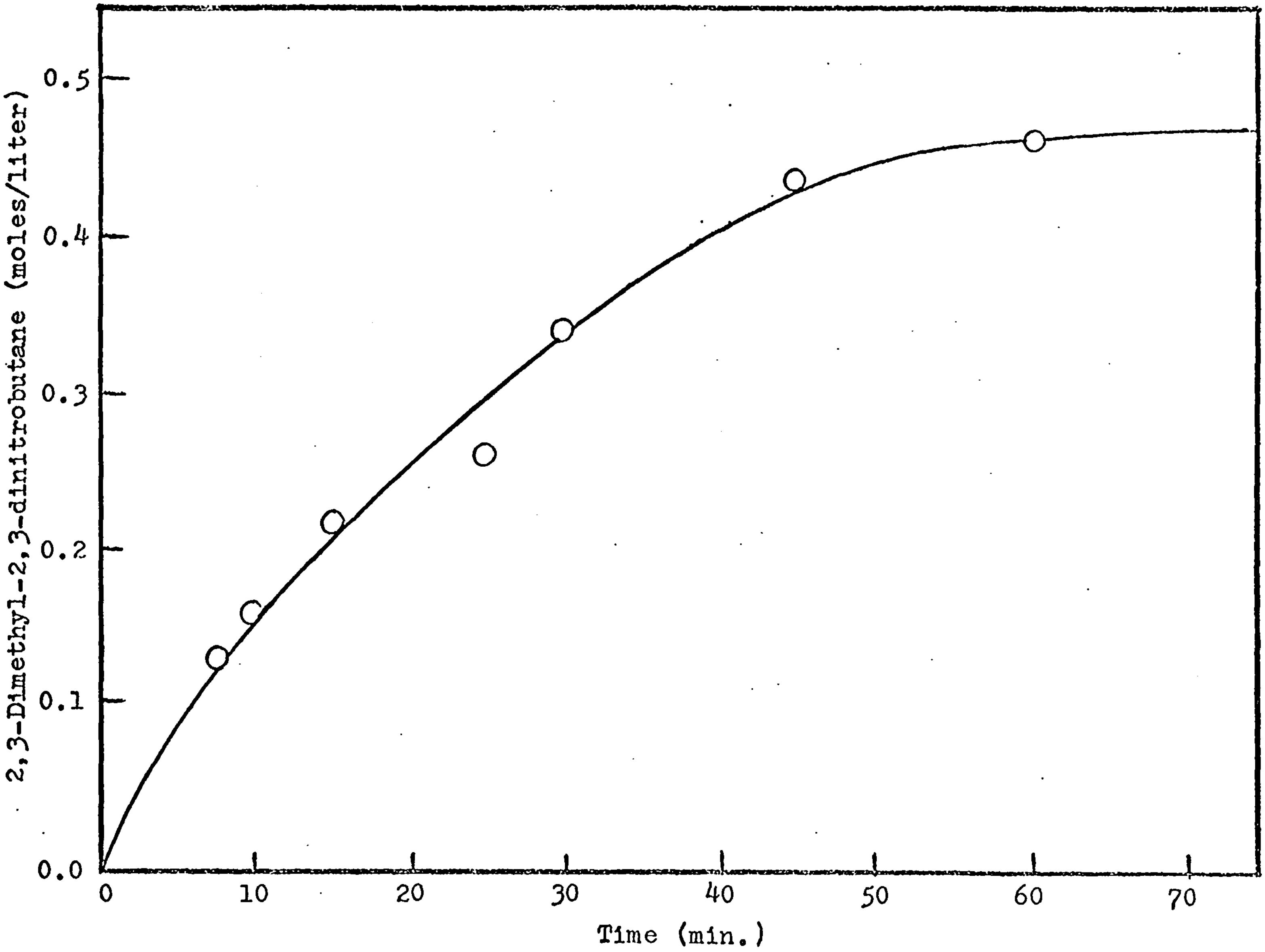

2-Chloro-2-nitropropane (moles/liter)
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
140
160
180
Time (min.)
A
B

Figure 8. Formation of 2,3-dimethyl-2,3-dinitrobutane in the reaction of 0.513 M potassium salt of 2-nitropropane with 0.513 M 2-bromo-2-nitropropane under nitrogen in ethanol and room light at ca. 30° C


2,3-Dimethyl-2,3-dinitrobutane (moles/liter)
0.0
0.1
0.2
0.3
0.4
0.5
0
10
20
30
40
50
60
70
Time (min.)

(Figure 9). Unlike the 2-chloro-2-nitropropane, there is a significant dark reaction for the bromo compound. Although this observation might at first be interpreted as resulting from a nonra[illegible]cess such as an S_N2 displacement of bromide by the anion, this possibility is ruled out by the fact that no detectable coupled product is formed in the presence of oxygen and no bromo compound is consumed (Figure 9) even though the rates of the oxidation and coupling reactions are of the same order of magnitude. Perhaps the bromo compound is more easily reduced than the chloro compound in an electron transfer process (reaction 23) due to its greater polarizability which offsets the electronegativity differences. Another possibility is that the bromo compound undergoes a dark reaction more readily than the chloro compound (e.g., reaction 30) which initiates the free radical process leading to formation of the dimer.

Figure 10 illustrates the effect of oxygen on the rate of consumption of 2-bromo-2-nitropropane. Note that in the absence of oxygen, the bromo compound rapidly reacts with the 2-nitro-2-propyl anion to give the coupled product, but when oxygen is bubbled through the reaction solution no bromo compound is consumed. In this particular plot the oxygen was removed and the reaction put under an atmosphere of nitrogen after approximately nine minutes. Shortly after ceasing the oxygen treatment it is observed that a rapid decrease in the concentration of bromo compound occurs. Not as much

Figure 9. Reaction of 0.256 M potassium salt of 2-nitropropane with 0.256 M 2-bromo-2-nitropropane in ethanol at 30°C

A. Illuminated in presence of oxygen

B. In dark and under nitrogen

C. Illuminated and under nitrogen

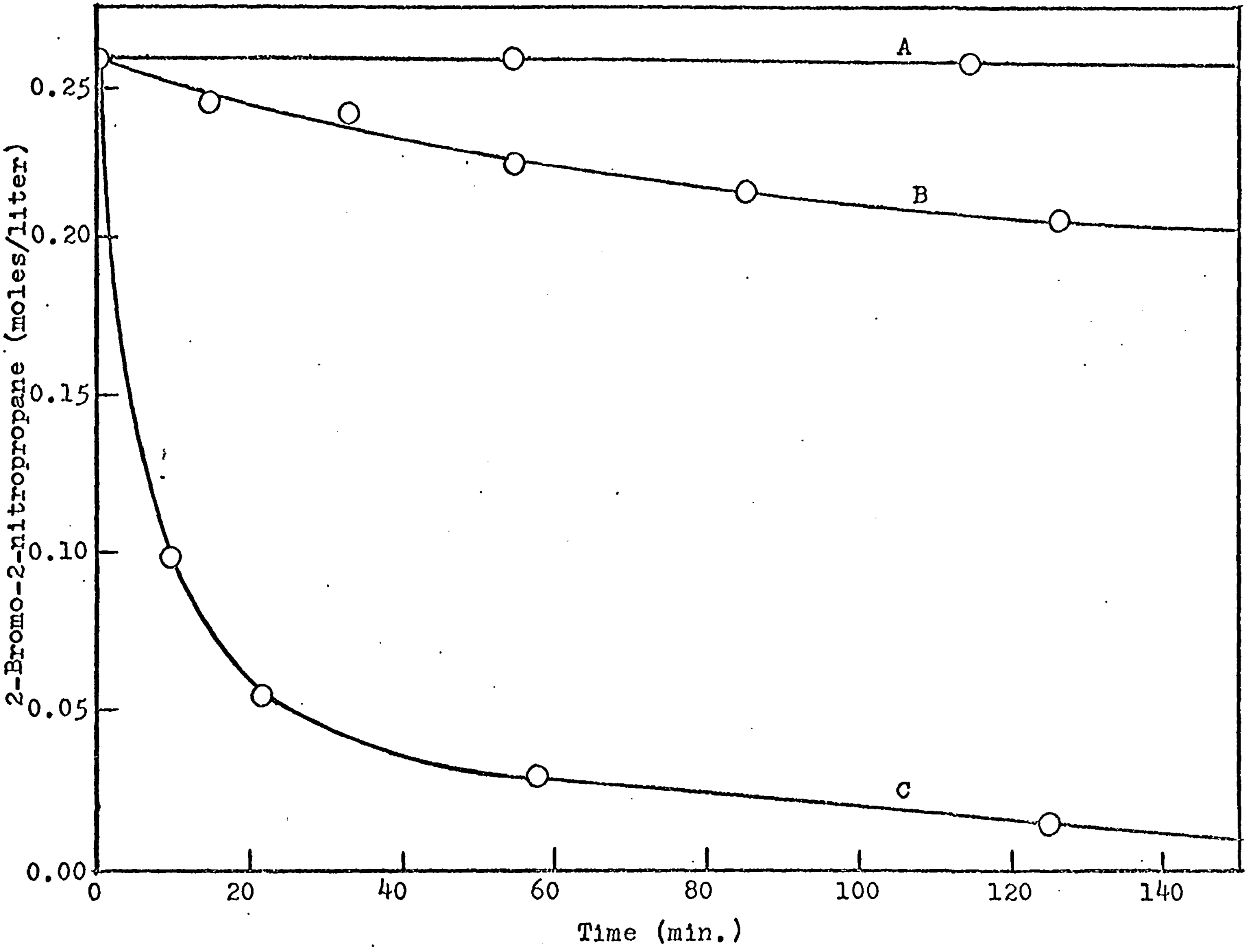
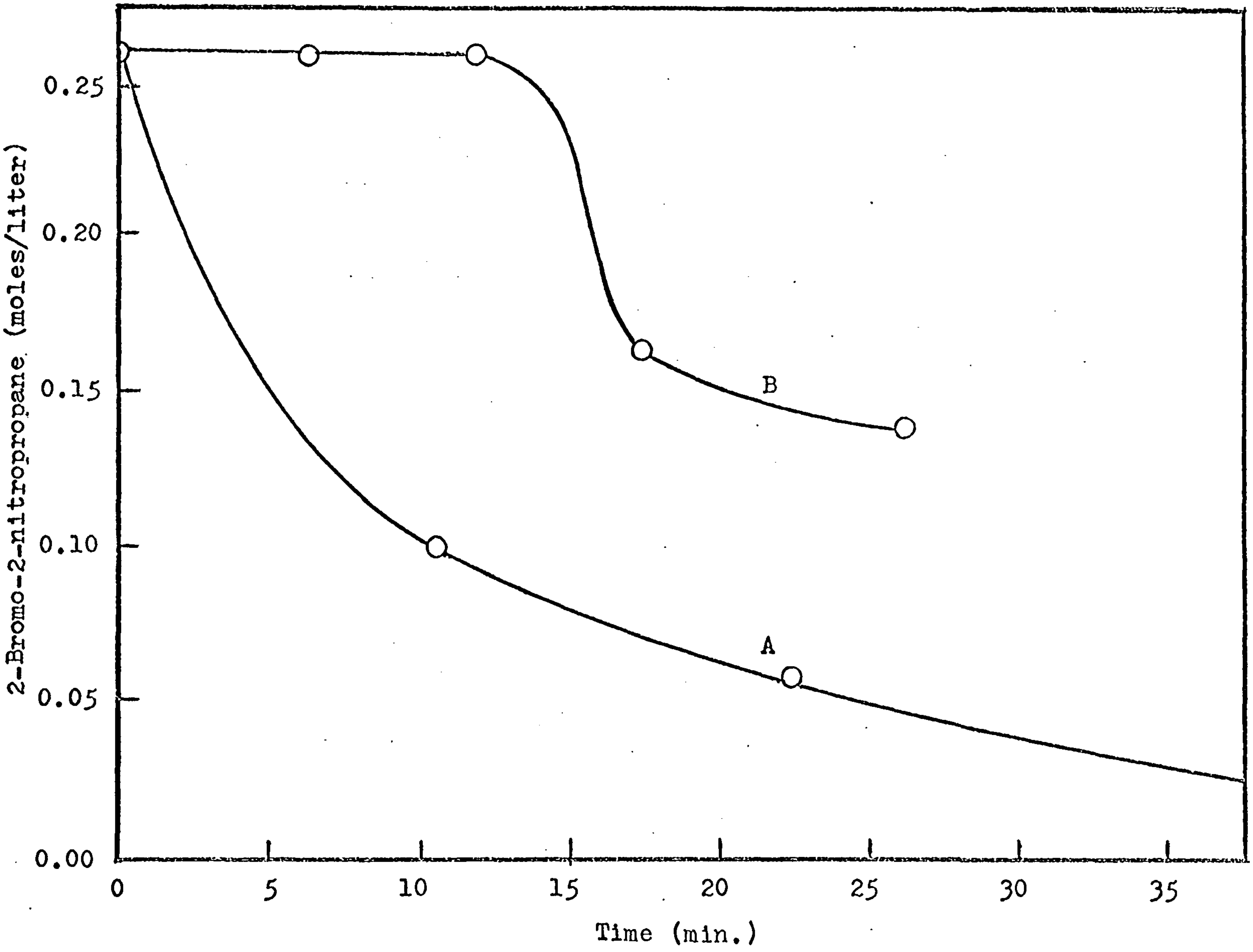

A
B
C
2-Bromo-2-nitropropane (moles/liter)
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
140
Time (min.)

Figure 10. Reaction of 0.256 M potassium salt of 2-nitropropane with 0.256 M 2-bromo-2-nitropropane in ethanol with illumination at 30° C

A. Under nitrogen for entire reaction

B. In presence of oxygen for initial state of reaction; placed under nitrogen after ca. 9 minutes



2-Bromo-2-nitropropane (moles/liter)
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
Time (min.)
A
B

2-bromo-2-nitropropane is consumed in the latter instance; this fact is undoubtedly attributed to a decrease in the concentration of anion as a result of its autocatalytic chain oxidation (reactions 16-22).

The catalytic effect of light and the inhibitory influence of oxygen suggested that the simple electron transfer coupling mechanism initially postulated (reactions 13-15) might not be the process actually occurring in the reaction of the 2-nitro-2-propyl anion with the 2-halo-2-nitropropanes. The observed results tended to suggest a free radical chain mechanism. A study of the effect of several free radical inhibitors on the course of the reaction was thus prompted.

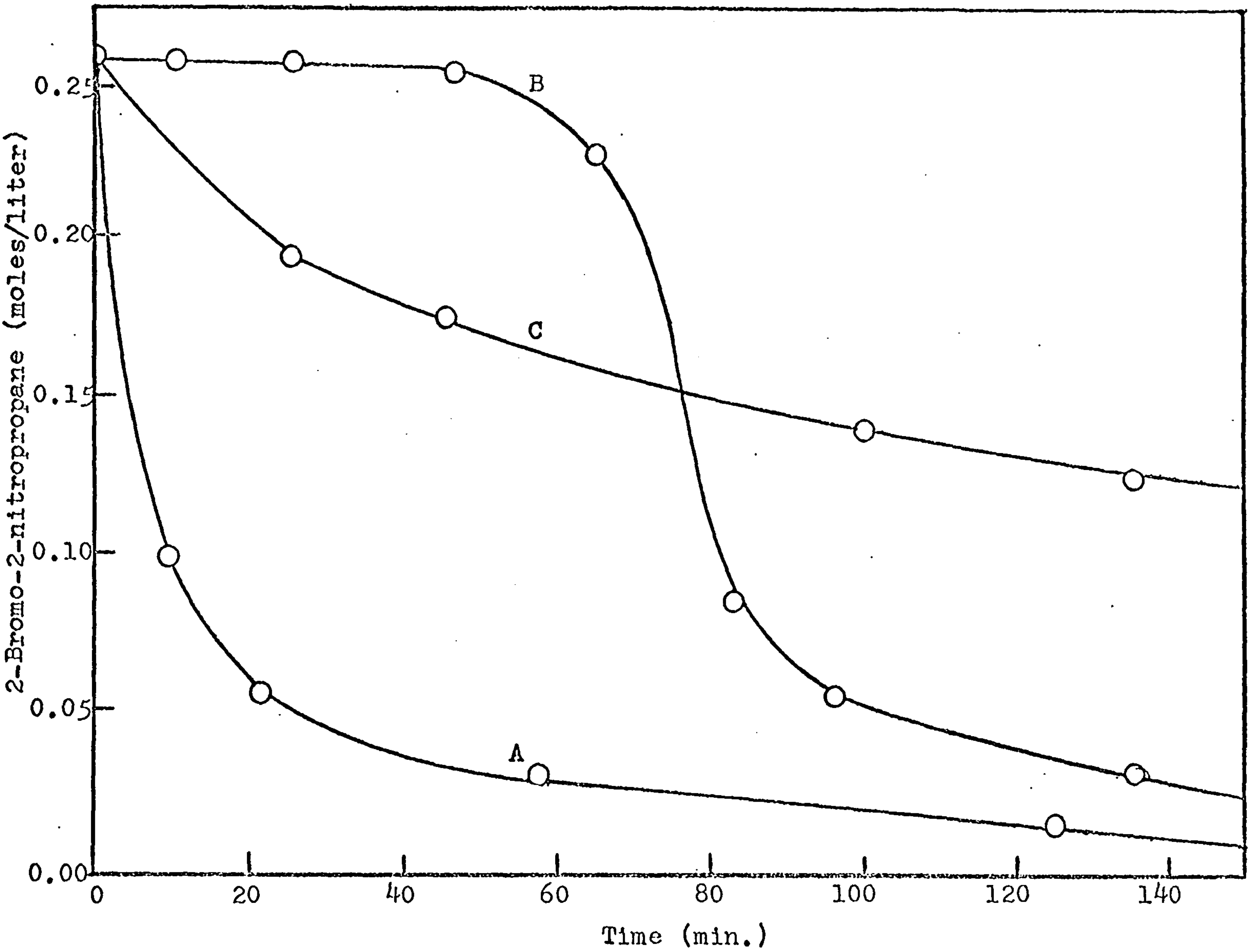
Figure 11 shows the effect of 2.1% of p-dinitrobenzene on the rate of consumption of 2-bromo-2-nitropropane. Note that this small amount of inhibitor retards the rate of reaction somewhat. The addition of 0.8% of hexaphenylethane to the reaction of the anion with 2-bromo-2-nitropropane results in a dramatic inhibitory effect (Figure 11). No change in the concentration of the bromo compounds occurs until after a time lapse of approximately 50 minutes after which a rapid reaction occurs. In the absence of inhibitor the reaction is more than 80% complete after 50 minutes. Similar results are obtained when p-dinitrobenzene and triphenylmethyl radical are used as inhibitors in the reaction of 2-chloro-2-nitropropane with the 2-nitro-2-propyl anion.

Figure 11. Reaction of 0.256 M potassium salt of 2-nitropropane with 0.256 M 2-bromo-2-nitropropane under nitrogen in ethanol 30° C

A. Illuminated

B. Illuminated and in presence of 0.002 M hexaphenylethane

C. Illuminated and in presence of 0.0053 M p-dinitrobenzene at 13° C

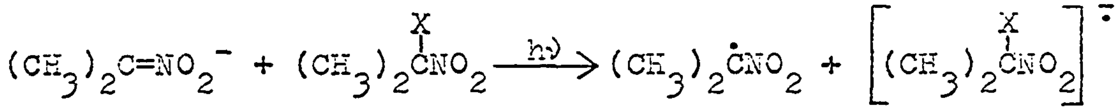

2-Bromo-2-nitropropane (moles/liter)
0.25
0.20
0.15
0.10
0.05
0.00
0
20
40
60
80
100
120
140
Time (min.)
A
B
C

These results clearly demand a chain mechanism. The mechanism originally suggested for the reaction under consideration (reactions 13-15), although free radical in nature, is not a chain mechanism and cannot account for the inhibitory effect of such small concentrations of free radical inhibitors.

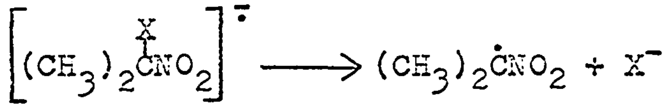
Although many chain mechanisms could possibly be written to account for the experimental results, two such mechanisms are especially appealing:

Scheme A: Radical displacement on carbon

Initiation



$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{X}{\overset{|}{C}}NO_2 \xrightarrow{h\nu} (CH_3)_2\dot{C}NO_2 + \left[(CH_3)_2\overset{X}{\overset{|}{C}}NO_2\right]^{\dot{-}} \qquad (31)$$



$$\left[(CH_3)_2\overset{X}{\overset{|}{C}}NO_2\right]^{\dot{-}} \longrightarrow (CH_3)_2\dot{C}NO_2 + X^- \qquad (32)$$

Propagation

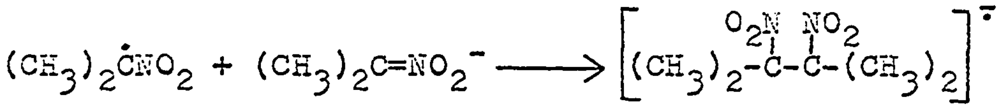
$$(CH_3)_2\dot{C}NO_2 + (CH_3)_2\overset{X}{\overset{|}{C}}NO_2 \longrightarrow (CH_3)_2\text{-}\overset{O_2N}{\overset{|}{C}}\text{-}\overset{NO_2}{\overset{|}{C}}\text{-}(CH_3)_2 + X\cdot \qquad (33)$$

$$(CH_3)_2C{=}NO_2^- + X\cdot \longrightarrow (CH_3)_2\dot{C}NO_2 + X^- \qquad (34)$$

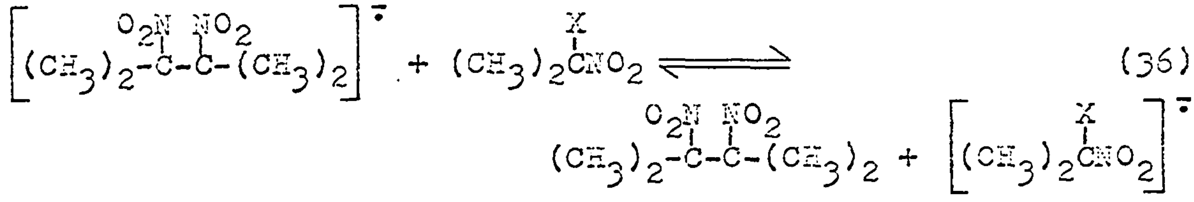
Scheme B: Radical coupling with anion

Initiation--same as in Scheme A

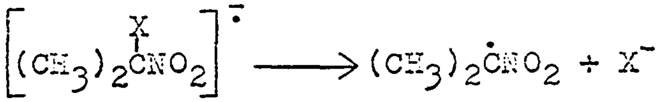
Propagation



$$(CH_3)_2\dot{C}NO_2 + (CH_3)_2C{=}NO_2^- \longrightarrow \left[(CH_3)_2\text{-}\overset{O_2N}{\overset{|}{C}}\text{-}\overset{NO_2}{\overset{|}{C}}\text{-}(CH_3)_2\right]^{\dot{-}} \qquad (35)$$



$$\left[(CH_3)_2-\overset{O_2N}{\overset{|}{C}}-\overset{NO_2}{\overset{|}{C}}-(CH_3)_2\right]^{\dot{-}} + (CH_3)_2\overset{X}{\overset{|}{C}}NO_2 \rightleftharpoons (CH_3)_2-\overset{O_2N}{\overset{|}{C}}-\overset{NO_2}{\overset{|}{C}}-(CH_3)_2 + \left[(CH_3)_2\overset{X}{\overset{|}{C}}NO_2\right]^{\dot{-}} \qquad (36)$$



$$\left[(CH_3)_2\overset{X}{\overset{|}{C}}NO_2\right]^{\dot{-}} \longrightarrow (CH_3)_2\dot{C}NO_2 + X^- \qquad (37)$$

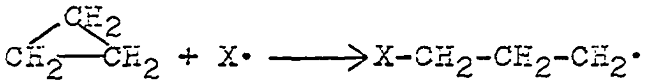
X = Cl or Br

In both schemes there is an initiation step which results in the formation of the 2-nitro-2-propyl radical. This radical is the chain-carrying species in both schemes. Although the initial formation of this radical is depicted in the scheme as occurring through an electron transfer process (reactions 31 and 32), there is no reason why other processes such as those discussed earlier (e.g., reactions 24-29) could not be the source of the initiating free radicals.

The key propagation step in Scheme A is reaction 33-- a radical displacement on a saturated carbon atom. Here the 2-nitro-2-propyl radical attacks a molecule of 2-halo-2-nitropropane to form a new carbon-carbon bond with the accompaning elimination of a halogen atom. This reaction is analogous to an S_N2 mechanism except a neutral free radical is the attacking species instead of a nucleophile and a halogen atom is the displaced species rather than a halide ion. The halogen atom formed quickly reacts with a molecule of anion in an electron transfer process generating halide ion and the 2-nitro-2-propyl radical (reaction 34) which can undergo reaction 33 and thus continue the chain.

There is little precedence in the literature for a free radical displacement on carbon. Only two systems are known where such a process occurs and both of these involve quite strained compounds. The addition of chlorine (12, 13), bromine (14), or iodine (15) to cyclopropane to yield 1,3-dihalopropane has been well documented as occurring with a radical displacement on carbon:

$$X_2 \xrightarrow{h\nu} 2X\cdot \qquad (38)$$



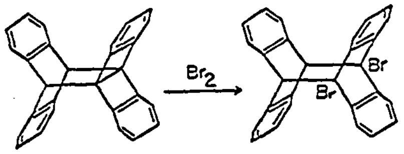
$$\text{cyclo-}(CH_2)_3 + X\cdot \longrightarrow X\text{-}CH_2\text{-}CH_2\text{-}CH_2\cdot \qquad (39)$$

$$X\text{-}CH_2\text{-}CH_2\text{-}CH_2\cdot + X_2 \longrightarrow X\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}X + X\cdot \qquad (40)$$

X = Cl, Br, or I

Cyclobutane gives no ring opening with chlorine atoms (12), a fact which is interpreted by Walling and Fredricks as reflecting the lack of "unsaturated" character in cyclobutane since the ring strains are comparable in cyclopropane and cyclobutane.

The only other case where a free radical displacement on carbon has been suggested is in the brominolysis of a "Dewar" anthracene (16):

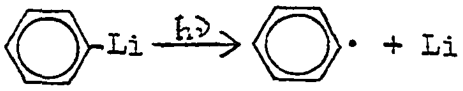


(41)

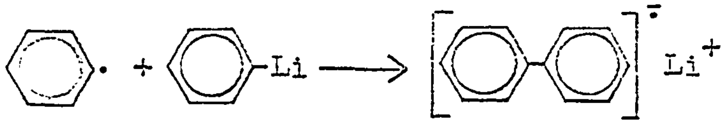
Reaction 41 is promoted by free radical initiators and inhibited by free radical traps. Applequist concludes that bromine adds to the "Dewar" anthracene by a free radical chain mechanism with bromine attacking the strained anthracene to break the 9,10-transannular bond. This process is analogous to the cleavage of cyclopropane by halogen atoms (reactions 38-40).

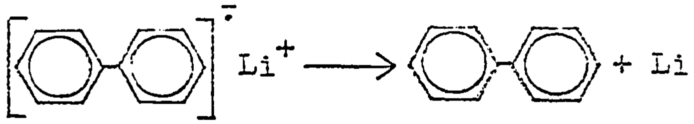
Scheme B (p. 37) invokes the coupling of a free radical with a molecule of 2-nitro-2-propyl anion as the key propagation step (reaction 35). The product of this reaction is the radical anion of the coupled dimer. This radical anion undergoes electron transfer with a molecule of 2-halo-2-nitropropane to produce the dimer and the radical anion of the halo compound (reaction 36) which eliminates halide ion to generate a new 2-nitro-2-propyl radical which can continue the chain process (reaction 37).

There is even less literature precedence for the radical coupling with an anion than there is for the radical displacement mechanism. The formation of biphenyl by irradiation of phenyllithium in ethyl ether has been studied by van Tamelen (17). Although not extensively investigated, it was suggested that a possible pathway leading to biphenyl may be the reaction of a phenyl radical with phenyllithium (reactions 42-44):



(42)

 (43)

 (44)

It was emphasized that this need not be a typical reaction since phenyllithium has been shown to be associated as dimers in ether (18, 19), and production of the phenyl radical by homolysis of the carbon-lithium bond would probably occur in the immediate vicinity of another molecule of phenyllithium. Direct formation of biphenyl, or synchronous generation and coupling of two phenyl radicals, from the dimer were not excluded as possible explanations for the observed results.

Kornblum has suggested that the 2-nitro-2-propyl radical will attack the nitrite ion to yield a radical anion (20):

$$(CH_3)_2\dot{C}NO_2 + NO_2^- \longrightarrow [(CH_3)_2C(NO_2)_2]^{\dot{-}} \qquad (45)$$

However, such a radical anion would be expected to be unstable with respect to elimination of nitrite ion just as the radical anions of 2-bromo- and 2-chloro-2-nitropropane eliminate halide ion (e.g., reaction 37). This conclusion is supported by the work of Adams, et al. (6) in which the radical anions of a series of nitro aliphatic compounds were investigated by electron spin resonance spectroscopy. Although the radical anion of 2-nitropropane is stable enough to be observed, no radicals were detected when 2-chloro-2-nitropropane or 2,2-dinitropropane were electrolytically reduced. *A priori*, one would have predicted that the radical anion of this latter compound would be more stable than that derived from 2-nitropropane since more delocalization of the unpaired spin could occur.

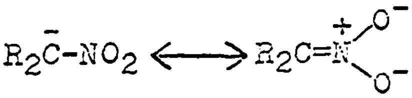
It can be seen that neither Scheme A nor B has much precedence in the literature. From the title of this thesis it should be obvious that the mechanism in which the radical couples with a carbanion (Scheme B) proved to be the mechanism operative in the reaction of the 2-nitro-2-propyl anion with 2-halo-2-nitropropanes. However, with only the experimental results thus far presented it is impossible to choose between Scheme A and B.

B. Reaction of 2-Nitro-2-propyl Anion with *p*-Nitrobenzyl Chloride

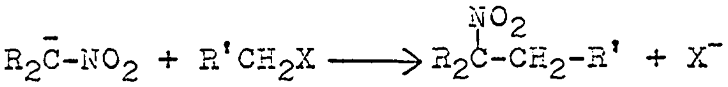
1. Literature review

The reaction of salts of aliphatic nitro compounds with various substituted benzyl compounds has long been recognized as possessing several unique features. This uniqueness derives from characteristics peculiar to both the anion and the benzyl compound.

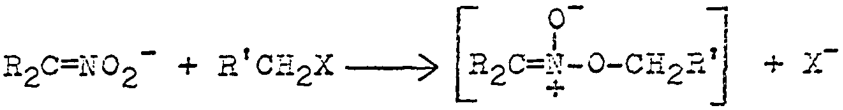
The anion derived from an aliphatic nitro compound is capable of covalency formation at either carbon or oxygen, i.e., it is an ambident anion:



$$R_2\bar{C}\text{-}NO_2 \longleftrightarrow R_2C{=}\overset{+}{N}\begin{smallmatrix}O^-\\O^-\end{smallmatrix} \qquad (46)$$

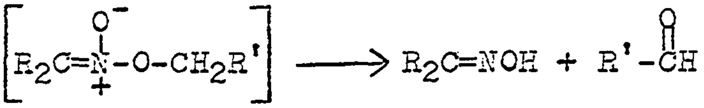


$$R_2\bar{C}\text{-}NO_2 + R'CH_2X \longrightarrow R_2\overset{NO_2}{\overset{|}{C}}\text{-}CH_2\text{-}R' + X^- \qquad (47)$$



$$R_2C{=}NO_2^- + R'CH_2X \longrightarrow \left[R_2C{=}\underset{+}{\overset{O^-}{\overset{|}{N}}}\text{-}O\text{-}CH_2R'\right] + X^- \qquad (48)$$

While the carbon alkylation product is stable (reaction 47), the nitronic ester formed (reaction 48) is never isolated. The corresponding carbonyl compound and oxime are obtained instead, and it is generally assumed that they arise from the nitronic ester (21, 22):

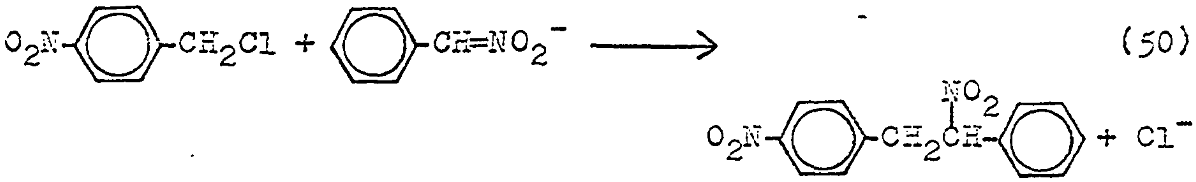


$$\left[R_2C{=}\underset{+}{\overset{O^-}{\overset{|}{N}}}\text{-}O\text{-}CH_2R'\right] \longrightarrow R_2C{=}NOH + R'\text{-}\overset{O}{\overset{\|}{C}}H \qquad (49)$$

However, nitronic esters have been synthesized and isolated from the reaction of nitroparaffin salts with trialkyloxonium fluoroborates (23).

Reactions of the salts of nitro compounds with aliphatic, allylic, and most benzylic halides usually produce carbonyl compounds and, in fact, serve as a useful means of preparing aldehydes and ketones (24). But in some instances the reaction results in carbon alkylations.

In 1945 Weisler and Helmkamp (21) investigated the action of some benzyl halides on salts of phenylnitromethane. No evidence for carbon-alkylation could be found when equimolar amounts of benzyl chloride and the sodium salt of phenylnitromethane were refluxed in absolute alcohol solution. That the reaction leads mainly, if not solely, to nitronic ester formation was shown by the isolation of a 76.5% yield of benzaldehyde and an 80% yield of the stereoisomeric benzaldoximes. On the other hand, when p-nitrobenzyl chloride was allowed to react under similar conditions, it was possible to separate not only p-nitrobenzaldehyde and a mixture of the benzaldoximes but also a 37% yield of a product which by analysis and chemical behavior was shown to be 1-nitro-2-(p-nitrophenyl)-1-phenylethane (reaction 50):


(50)

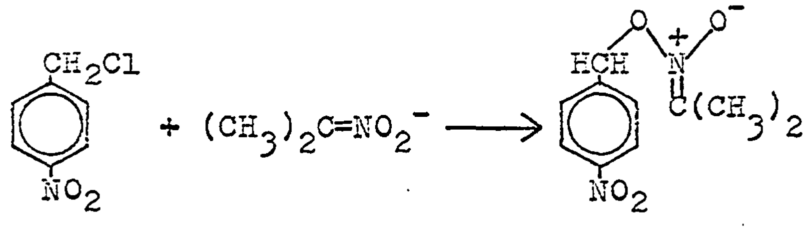
No reaction took place when the mercury derivative of phenylnitromethane was treated with alcohol, ether, and benzene solutions of p-nitrobenzyl chloride.

2,4-Dinitrobenzyl chloride was reacted in anticipation of producing a better yield of carbon substituted product. It was found that when this halide was allowed to react in boiling ethanol solution with the sodium salt of phenylnitromethane, carbon alkylation and oxygen alkylation occurred at nearly the same rate. It was not possible, however, to isolate the benzylated derivatives initially produced. Apparently 2-(2,4-dinitrophenyl)-1-nitro-1-phenylethane readily loses nitrous acid under the conditions of the experiment forming 2,4-dinitrostilbene while the nitronic ester undergoes the usual disproportionation. The yield of the stilbene was 46.6% and that of the benzaldoximes 45.5%.

In contrast to the action of p-nitrobenzyl chloride and 2,4-dinitrobenzyl chloride, the reaction of p-cyanobenzyl chloride resulted observedly only in oxygen alkylation. From the reaction mixture, p-cyanobenzaldehyde and the benzaldoxime were separated in approximately 80% yields.

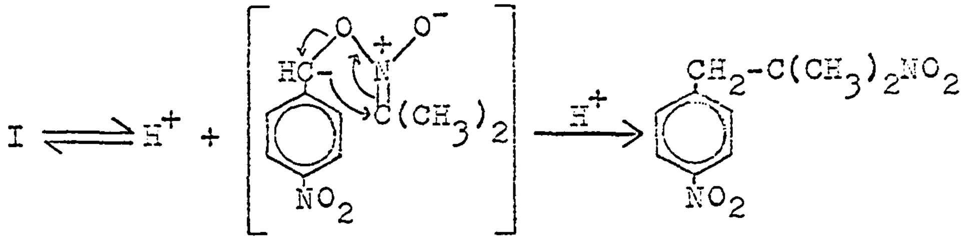
The first report of the uniqueness of p-nitro- and 2,4-dinitrobenzyl chlorides in reaction with the salts of phenylnitromethane initiated considerable investigation of the reaction. Hass and Bender (22) investigated the reaction of the sodium salt of 2-nitropropane with a series of benzyl halides utilizing a uniform procedure. The results of the alkylation reaction of nine substituted benzyl halides which had as para substituents CH_3, Br, $CH_3O\overset{\overset{O}{\|}}{C}$, $CH_3\overset{\overset{O}{\|}}{C}$, CN, CF_3, and $\overset{+}{N}(CH_3)_3$, and NO_2 indicated that the reaction produced carbon alkylation only in the isolated case of p-nitrobenzyl chloride. In all the other cases the corresponding benzaldehydes were produced in 68-77% yields and no carbon alkylate was detected. These results led the authors to seek some explanation for the anomalous behavior of p-nitrobenzyl chloride in the reaction (25).

The second-order rates of the four alkylation reactions (both carbon and oxygen alkylation considered) involving the lithium salt of 2-nitropropane and o-, m-, and p-nitrobenzyl chlorides and benzyl chloride were determined and compared with the relative rates of the four halides in another second-order reaction, the reaction with potassium iodide in acetone. The good correlation, coupled with the evidence that the rate determining step in oxygen alkylation is the formation of the nitronic ester, led these authors to the conclusion that the rate determining step in both oxygen and carbon alkylation is the formation of a nitronic ester intermediate. Another parallelism was noted between those benzyl halides which showed carbon alkylation with 2-nitro-2-propyl anion and those exhibiting stilbene formation in the Williamson reaction. Since the mechanism proposed for stilbene formation involves the ready removal of a benzylic hydrogen facilitated by the presence of an o- or p-nitro group, it was concluded that the case of removal of a benzylic hydrogen is an important factor in the production of carbon alkylation. The following mechanism was proposed:



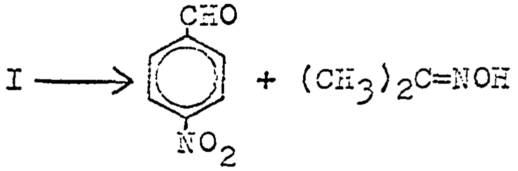
(51)

I



II

(52)



(53)

The first step in both oxygen and carbon alkylation is the formation of the nitronic ester, I (reaction 51). When oxygen alkylation occurs, p-nitrobenzaldehyde and acetoxime are produced by cleavage of the nitronic ester along with a hydrogen shift (reaction 53). When carbon alkylation occurs, the resonance stabilized carbanion, II, is formed as an intermediate by the ionization of a benzylic hydrogen of the nitronic ester. Following the ionization, an internal nucleophilic displacement reaction occurs producing the carbon alkylated product (reaction 52). Thus, there are two competing reactions of a nitronic ester such as I. The relative amounts of the final products are determined by the relative rates of the competing cleavage and ionization reactions. Since the rate of the ionization reaction is a function of the position of the ionization equilibrium, those factors in the structure of the reactants which shift the equilibrium of the ionization reaction will shift the direction of the alkylation.

A time lapse occurred between the publication of this mechanism and any further work on the reaction mechanism. In 1961, however, Kornblum and co-workers (26) found that the uniqueness of the p-nitrobenzyl system depends not only on the p-nitro group but also on the leaving group. Table 1 summarizes their results. It is seen that whereas p-nitrobenzyl chloride gives 95% carbon alkylation, p-nitrobenzyl iodide gives 81% oxygen alkylation. The results from Table 1 demonstrate that carbon alkylation predominates in the p-nitrobenzyl system only when the leaving group is one which is difficultly displaced. In contrast, the unsubstituted benzyl system shows no leaving group effect. The reactions of benzyl chloride, bromide, iodide, or tosylate with the lithium salt of 2-nitropropane in DMF all give 82-84% yield of benzaldehyde

Table 1. Nature of reaction of p-$O_2NC_6H_4CH_2X$ with the lithium salt of 2-nitropropane in DMF (-16°C) as a function of X

X	% Carbon Alkylation	% Oxygen Alkylation
$^{+}NMe_3$	93	0
C_6Cl_5COO	93	0
Cl	95	1
OTos	40	32
Br	17	65
I	7	81

and about 1% yield of the carbon alkylate, 2-benzyl-2-nitropropane (26).

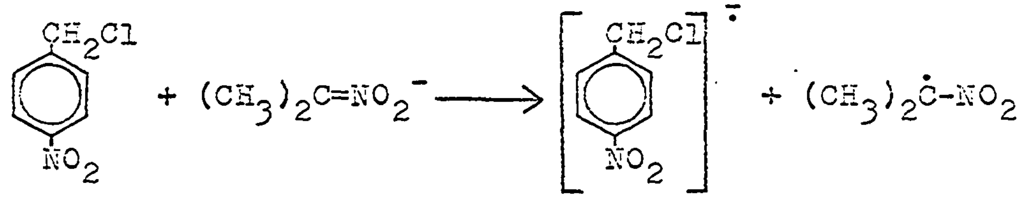
It was also noted that when carbon alkylation in the p-nitrobenzyl system occurs to the essential exclusion of oxygen alkylation (i.e., when the leaving group is NMe_3, pentachlorobenzoate, or chloride), the reaction rate is much faster than for the corresponding unsubstituted benzyl compound (Table 2). It is seen from the table that when the p-nitrobenzyl group is unable to effect carbon alkylation of the 2-nitro-2-propyl anion, it simultaneously fails to produce a large increase in rate relative to the corresponding benzyl compound.

Table 2. Relative reaction rates as a function of leaving group, X

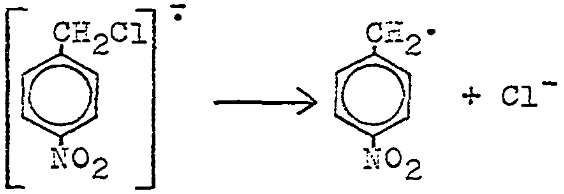
X	Relative Reaction Rates $\frac{p\text{-}O_2NC_6H_4CH_2\text{-}X}{C_6H_5CH_2\text{-}X}$
$^+NMe_3$	>100
C_6Cl_5COO	>100
Cl	>100
OTos	8
Br	6
I	3

On the basis of these findings it was proposed that oxygen alkylation, the usual mode of reaction of a nitroparaffin anion, derives simply from nucleophilic displacement by the oxygen of the anion on the benzylic carbon. But in the p-nitrobenzyl series, when the leaving group is one which is difficultly displaced, a second mode of attack by the nitroparaffin anion has a chance to compete, and it is this second process which is productive of carbon alkylation. No attempt was made to describe this alternate mode of attack to produce the carbon alkylated product (26). However, these results clearly exclude the earlier proposed mechanism by Hass and Bender (reactions 51-53) since the relative amounts of oxygen and carbon alkylated products should be independent of the nature of the leaving group if indeed the nitronic ester is the precursor to both sets of products.

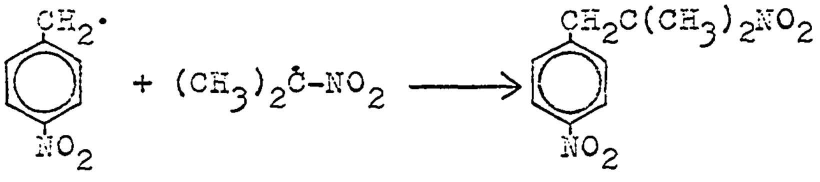
In 1965 Kornblum, et al. (27) proposed a new mechanism for the reaction of o- and p-nitrobenzyl chloride with the lithium salt of 2-nitropropane utilizing earlier data and newly acquired results. The o-nitrobenzyl system, like the p-nitrobenzyl system, shows a pronounced leaving group effect. Furthermore, since 31% carbon alkylated and 52% oxygen alkylated products are obtained, it is clear that the o-nitro group is considerably less effective at fostering carbon alkylation than the p-nitro group. In the o-, or the m-, or the p-nitrobenzyl series, on passing from the chloride to the bromide to the iodide as leaving groups, it was found that the rate of oxygen alkylation increases by a factor of 1000. In contrast to this, the rate of carbon alkylation only increases by a factor of seven. This shows that the rate of oxygen alkylation is strongly dependent on the leaving group; whereas the rate of carbon alkylation is relatively insensitive to the leaving group. The large spread in the rate of oxygen alkylation is taken as support for this author's earlier proposed S_N2 mechanism for oxygen alkylation (26). The slower rate of carbon alkylation in the *ortho* case and the immeasurably slow reaction in the *meta* system as contrasted with the rapid reaction of *p*-nitrobenzyl chloride indicates that electron acceptance by the nitro group is an important aspect of the carbon alkylation process. The following radical anion mechanism was postulated:



(54)

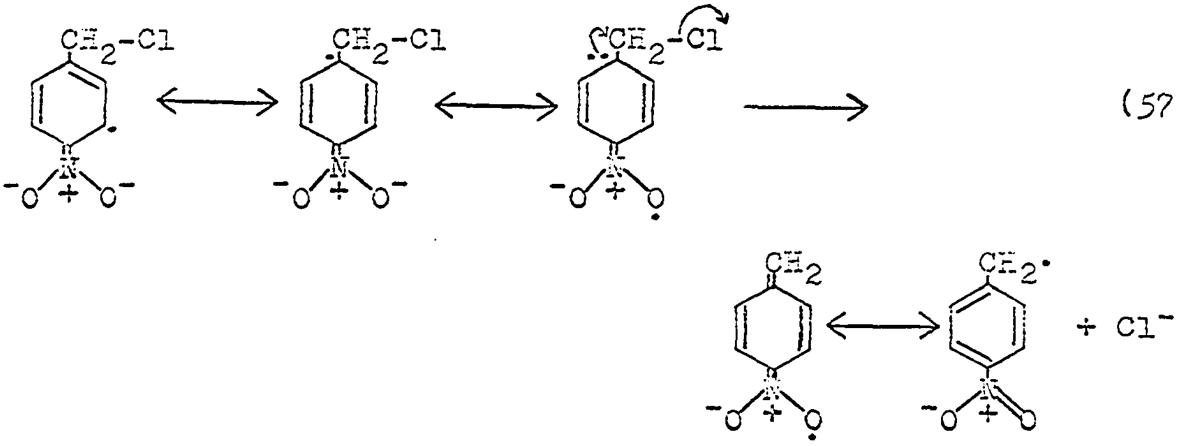


(55)



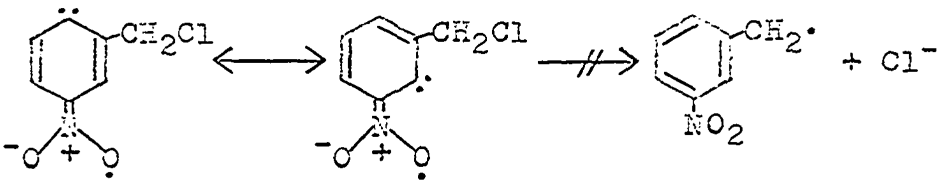
(56)

The first step involves an electron transfer from the 2-nitro-2-propyl anion to *p*-nitrobenzyl chloride to form the radical anion of this latter compound along with the 2-nitro-2-propyl radical (reaction 54). The radical anion then eliminates chloride ion to form the p-nitrobenzyl radical (reaction 55). The final product is produced by simple combination of the two neutral free radicals (reaction 56). Loss of chloride ion from the radical anion (reaction 55) to give the p-nitrobenzyl radical can be better appreciated by considering the various resonance structures in more detail:



(57)

It is seen that the ejection of the chloride ion is simply an elimination reaction producing an olefin. The slower rate of carbon alkylation in o-nitrobenzyl chloride reflects the steric inhibition of resonance to which the nitro group is subject thus making the ortho isomer less likely to accept an electron in a transfer process. This conclusion is substantiated by the observation that o-nitrotoluene is significantly more difficult to reduce than p-nitrotoluene (28). The low reactivity of m-nitrobenzyl chloride is explained as a result of the inability of the m-nitrobenzyl chloride radical anion to lose chloride ion by an internal elimination analogous to that available to the p-nitrobenzyl chloride:



(58)

The reason for this difference in behavior of the m- and the p-nitrobenzyl chloride radical anions probably derives from two factors. First, the p-nitrobenzyl radical is undoubtedly the more stable radical of the two since the nitro substituent is located in a position to participate in delocalization of the unpaired electron. Secondly, electron spin resonance results of nitrobenzene radical anion and derivatives invariably show appreciable electron densities in the positions ortho and para to the nitro group and only small values in the meta positions, in agreement with resonance structures such as depicted in reactions 57 and 58 (28). The significance of such resonance structures has received support from molecular orbital calculations (29). Such structures do not place the pair of electrons in a favorable arrangement for the internal elimination of chloride ion in the m-nitrobenzyl case (reaction 58).

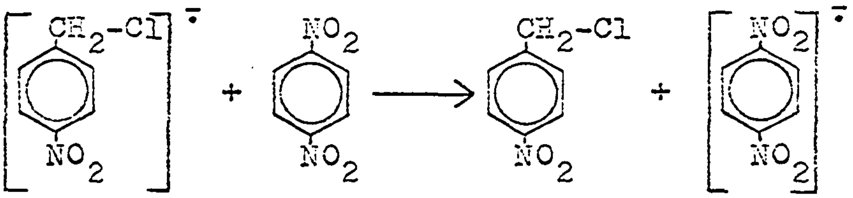
Supposed support for this mechanism (reactions 54-56) was derived from electron spin resonance studies in which radicals were detected when the reaction was conducted in the cavity of the spectrometer. However, the authors themselves admit that such a finding does not constitute a demonstration of the radical anion mechanism. The results do show that electron transfer from the lithium salt of 2-nitropropane to nitroaromatic compounds does occur under the reaction conditions and thus lends support to the first step (reaction 54) of the radical anion mechanism. These results are in agreement with those of Russell and coworkers who found that the nitrobenzene radical anion is produced on treating nitrobenzene with nitroparaffin salts (30).

More conclusive proof for the radical anion mechanism was obtained from a study of the effect of nitroaromatic compounds on the reaction of the anion with p-nitrobenzyl chloride. Table 3 shows that the addition of nitrobenzene, or m- or

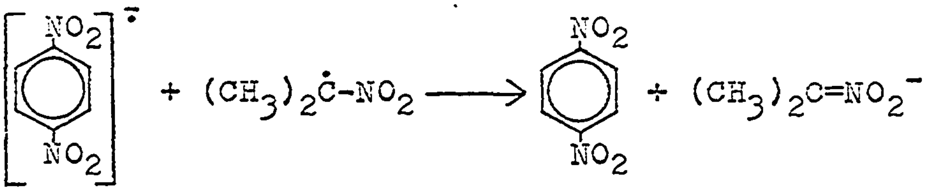
Table 3. The influence of nitroaromatics on the reaction of p-nitrobenzyl chloride (10 mmoles) with the lithium salt of 2-nitropropane (21 mmoles)

Added Nitroaromatic (mmoles)	% Yield Carbon Alkylate	% Yield Oxygen Alkylate
None	92	6
$C_6H_5NO_2$ (40)	84	7
m-$(NO_2)_2C_6H_4$ (10)	61	29
m-$(NO_2)_2C_6H_4$ (20)	40	48
p-$(NO_2)_2C_6H_4$ (2)	6	88
p-$(NO_2)_2C_6H_4$ (10)	2	72

p-dinitrobenzene causes a decrease in the amount of carbon alkylated product and a corresponding increase in the amount of oxygen alkylated product. It is noted that the effectiveness of the nitroaromatics in suppressing carbon alkylation decreases in the order p-$(NO_2)_2C_6H_4 >$ m-$(NO_2)_2C_6H_4 > C_6H_5NO_2$ and that this order coincides with their case of reduction (31). The inhibition of carbon alkylation by the nitroaromatics listed in Table 3 was explained as resulting from an electron transfer from the radical anion of p-nitrobenzyl chloride to the nitroaromatic before loss of chloride occurred:

 (59)

From Table 3 it is apparent that each p-dinitrobenzene is capable of repeatedly interrupting the carbon alkylation process since only 2.0 mmoles are required to decrease the yield of carbon alkylate by 8.2 mmoles. The authors rationalize this finding by assuming that the p-dinitrobenzene radical anion gives an electron to the 2-nitro-2-propyl radical generated in the first step of the reaction (reaction 54):

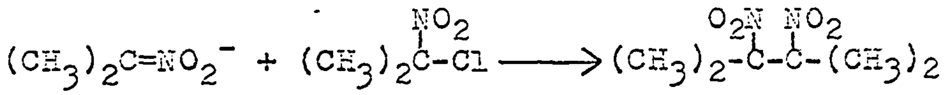
 (60)

Probably the weakest point in the mechanism is the explanation accounting for the absence of symmetrical coupling product, 2,3-dimethyl-2,3-dinitrobutane (from the 2-nitro-2-propyl radical) and p,p'-dinitrobibenzyl (from the p-nitrobenzyl radical). Here Kornblum argues that the two radicals must be formed in the immediate vicinity of each other and couple cleanly as in reaction 56. A π-complex is invoked in which the p-nitrobenzyl chloride radical anion acts as a donor toward the 2-nitro-2-propyl radical. When the radical anion ejects chloride ion the p-nitrobenzyl radical formed couples immediately with the 2-nitro-2-propyl radical. A simple solvent cage effect is ruled out by the fact that almost identical yields of carbon alkylate are formed in two different solvents, dimethylformamide and ethanol. The authors also admit that it is illogical to argue that neither the p-nitrobenzyl chloride radical anion nor the 2-nitro-2-propyl radical can leak out of a solvent cage while p-dinitrobenzene can enter it to intercept the radical anion.

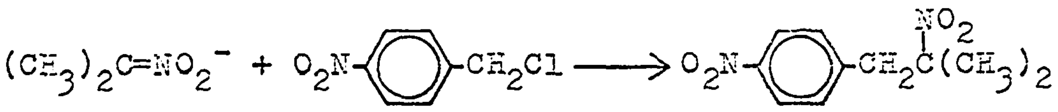
2. Results and discussion

It will be noted that the mechanism proposed by Kornblum, et al. (27) (reactions 54-56) is identical to that originally postulated for the reaction of the 2-nitro-2-propyl anion with 2-halo-2-nitropropane (reactions 13-15). In the latter case, however, all the neutral free radicals formed are identical and only a symmetrical coupled product could possibly result, and there is no need to postulate a π-complex of the kind proposed by Kornblum. But it was shown that the simple electron transfer process could not be operative for the reaction of the 2-nitro-2-propyl anion with 2-halo-2-nitropropanes. The similarity between this reaction and the reaction of the anion with p-nitrobenzyl chloride prompted the investigation of this latter reaction.

Since p-nitrobenzyl chloride can be considered a phenylog of chloronitromethane, it would not be suprising if the mechanisms of reaction of the 2-nitro-2-propyl anion with p-nitrobenzyl chloride and 2-chloro-2-nitropropane were quite similar:



$$(CH_3)_2C{=}NO_2^- + (CH_3)_2\overset{NO_2}{\overset{|}{C}}{-}Cl \longrightarrow (CH_3)_2{-}\overset{O_2N}{\overset{|}{C}}{-}\overset{NO_2}{\overset{|}{C}}{-}(CH_3)_2 \qquad (61)$$



(62)

In this section it will be shown that, indeed, the same mechanism is occurring in both reactions. Moreover, as a result of the study of the p-nitrobenzyl system, it is possible to choose between Scheme A and B (p. 37).

The reaction of the 2-nitro-2-propyl anion with p-nitrobenzyl chloride in ethanol was investigated utlizing the original technique of performing the reaction both in the presence and absence of molecular oxygen. In the absence of oxygen, yields of greater than 90% of carbon alkylated product are formed while in the presence of oxygen no detectable amount of coupled product is formed. Figure 12 shows that oxygen is absorbed to the extent of approximately 0.5 mole per mole of 2-nitro-2-propyl anion. When the reaction is performed in the presence of oxygen, the concentration of p-nitrobenzyl chloride remains unchanged. It is seen, therefore, that oxygen has the same effect on this reaction as it did on the reaction of the anion with the 2-halo-2-nitropropanes. The 2-nitro-2-propyl anion is oxidized via an autocatalytic chain mechanism to acetone and nitrite ion. The p-nitrobenzyl chloride behaves as a catalyst for the oxidation process and is not consumed in the reaction.

Figure 12 also demonstrates the effect of light on the rate of oxygen absorption. Note that in the dark there is a negligible oxygen uptake even after extended periods of time. When the reaction vessel is irradiated, however, approximately 0.5 mole equivalent of oxygen is reacted quite rapidly. The observation that no oxygen is absorbed in the dark in this case apparently indicates that one or more dark reactions producing radicals are occurring in the 2-chloro- and 2-bromo-2-nitropropane systems for there is oxygen uptake even in the dark (Figures 5 and 6).

A plot of p-nitrobenzyl chloride concentration versus time is given in Figure 13. It is seen that no chloro compound is consumed when the reaction is conducted in the presence of oxygen. Likewise, no chloro compound reacts in the dark even

Figure 12. Reaction of 0.170 M (2.56 mmoles) lithium salt of 2-nitropropane and 0.170 M (2.56 mmoles) *p*-nitrobenzyl chloride with oxygen in ethanol at ca. 30°C

A. Dark

B. Illuminated

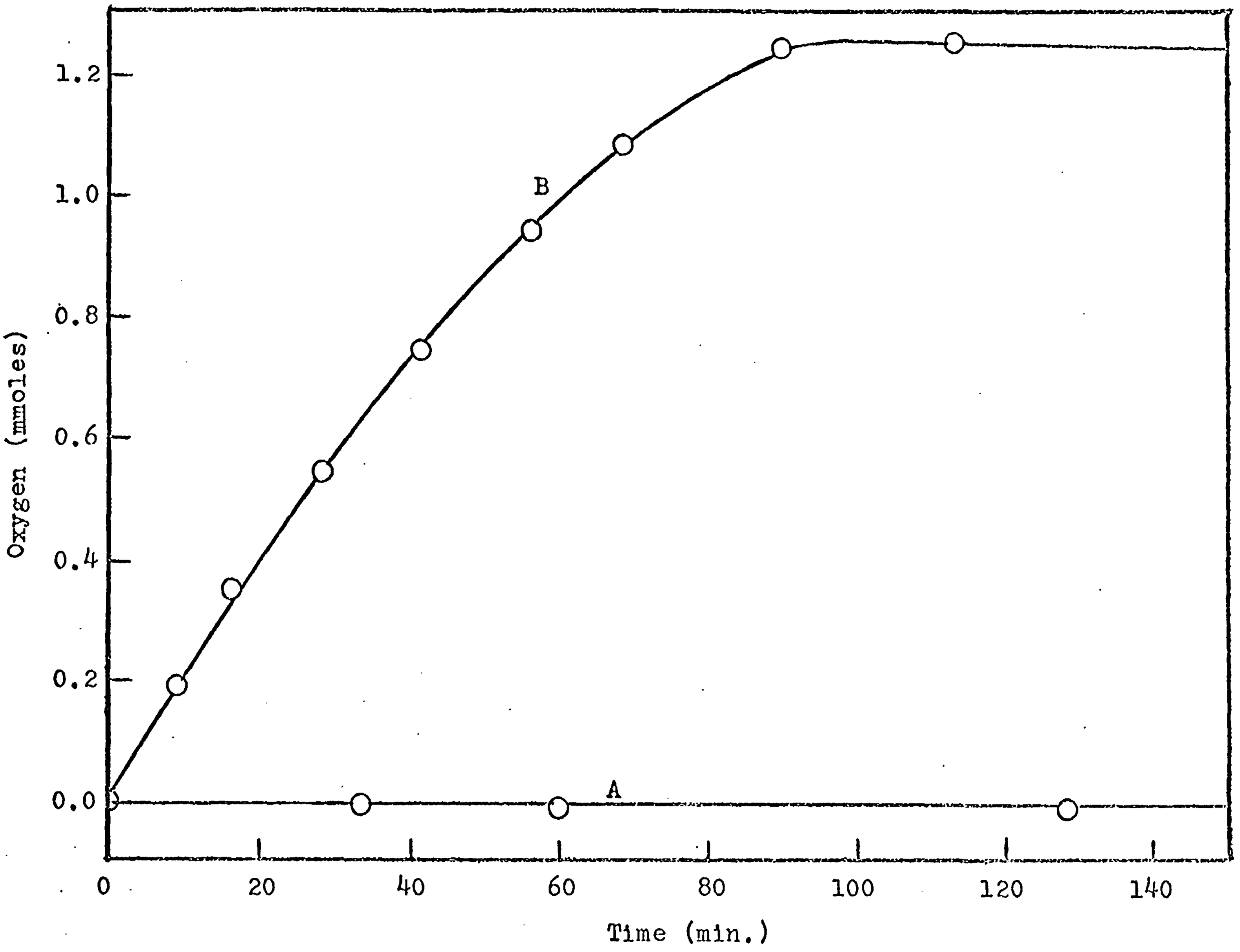
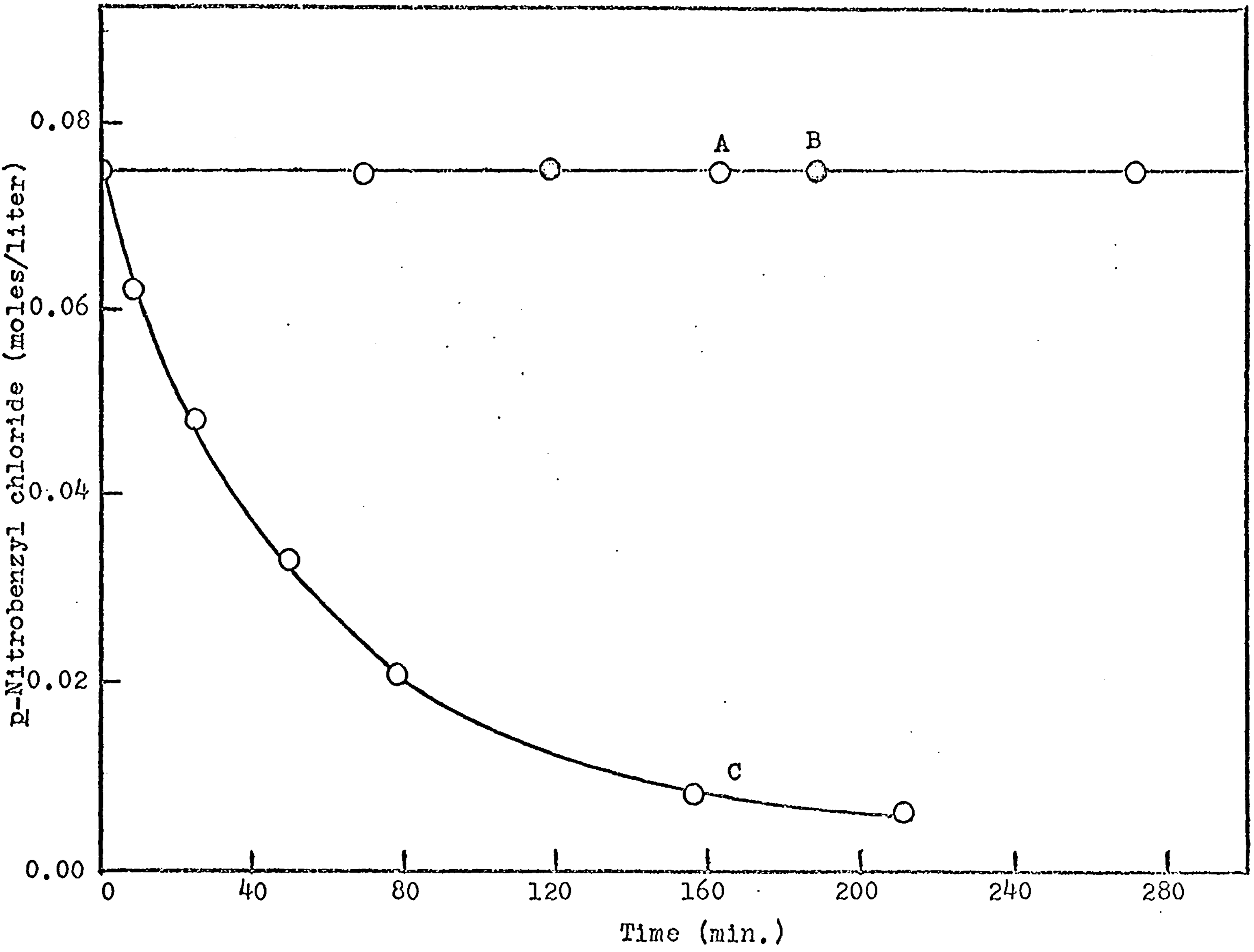

Oxygen (mmoles)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Time (min.)
0
20
40
60
80
100
120
140
A
B

Figure 13. Reaction of 0.075 M lithium salt of 2-nitropropane with 0.075 M *p*-nitrobenzyl chloride in ethanol at 0°C

A. In dark and under nitrogen

B. Illuminated in presence of oxygen

C. Illuminated and under nitrogen


p-Nitrobenzyl chloride (moles/liter)
0.08
0.06
0.04
0.02
0.00
A
B
C
0
40
80
120
160
200
240
280
Time (min.)

if the reaction is performed under an inert nitrogen atmosphere. The halogen compound does react quite rapidly when the nitrogen reaction is irradiated. Again, just as in the case of the reaction of the 2-nitro-2-propyl anion with 2-halo-2-nitropropane, light has a profound catalytic effect on both the oxidation reaction and the reaction producing the coupled product.

Kornblum has reported that the formation of carbon alkylated product in the reaction of the lithium salt of 2-nitropropane in dimethylformamide (DMF) is not a light-induced process (27). Figure 14 shows that in ethanol there is a profound increase in the rate of formation of coupled product when the reaction is photolyzed. Indeed there is very little, if any, reaction occurring in the dark. Figure 15 demonstrates that the reaction is also catalyzed by light in DMF at 0°C, Kornblum's conditions (27). It is apparent, though, that here there is a fast rate of reaction even in the dark. The quite drastic effect of solvent on the rate of reaction is not unexpected since in ethanol the 2-nitro-2-propyl anion is highly solvated whereas in aprotic DMF the anion is more "free" and capable of interaction with its chemical partner. In spite of the rapid dark reaction, the carbon alkylated coupled product is formed even faster when the reaction solution is irradiated. In view of the rapid reactions which occur in DMF it is puzzling why Kornblum allows his solutions to react for 48 hours before working them up (27).

Figure 14. Formation of coupled product in the reaction of 0.075 M lithium salt of 2-nitropropane with 0.075 M p-nitrobenzyl chloride under nitrogen and in ethanol at 0° C

A. Dark

B. Illuminated

C. Illuminated in presence of 0.0032 M p-dinitrobenzene

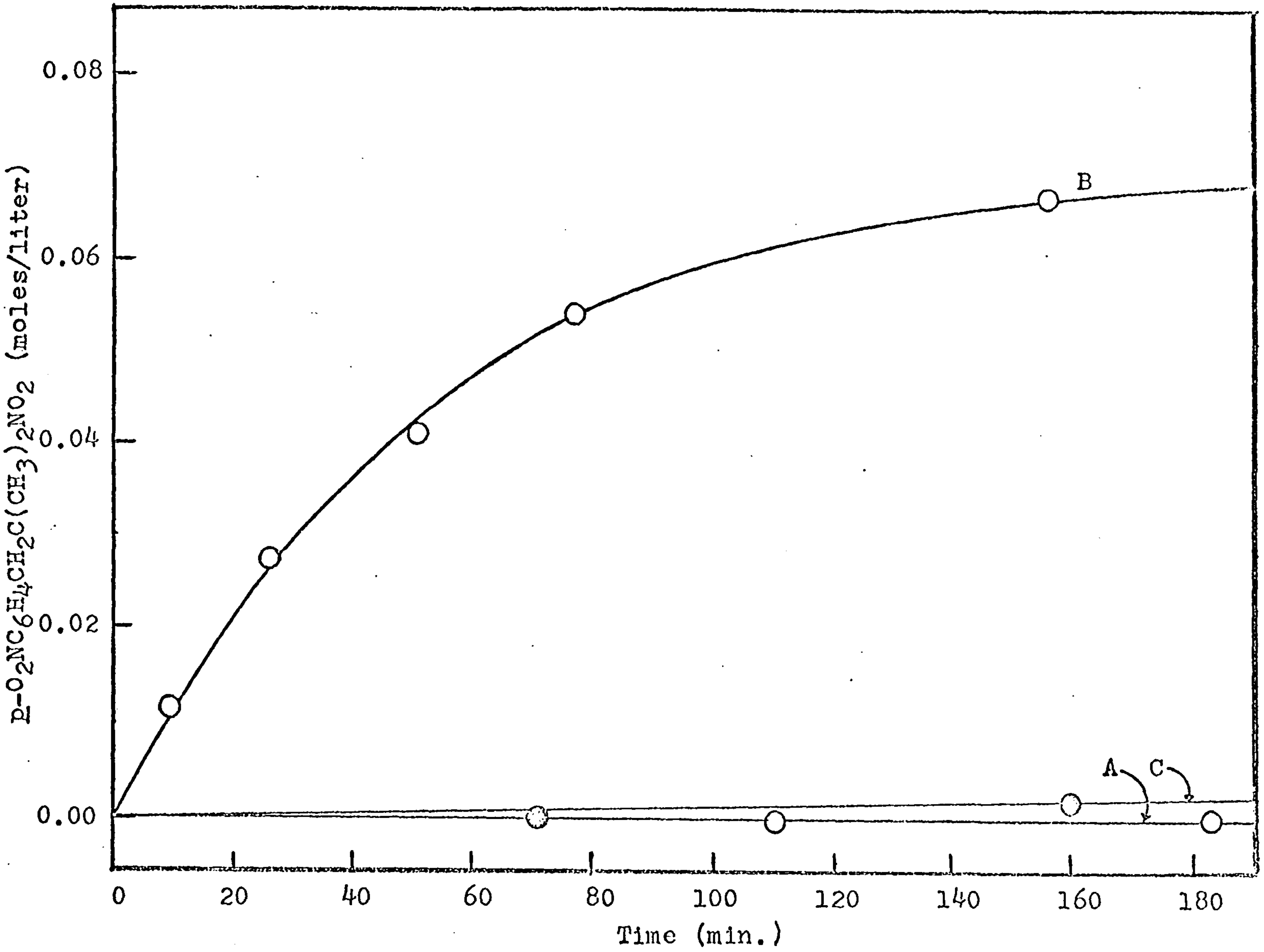
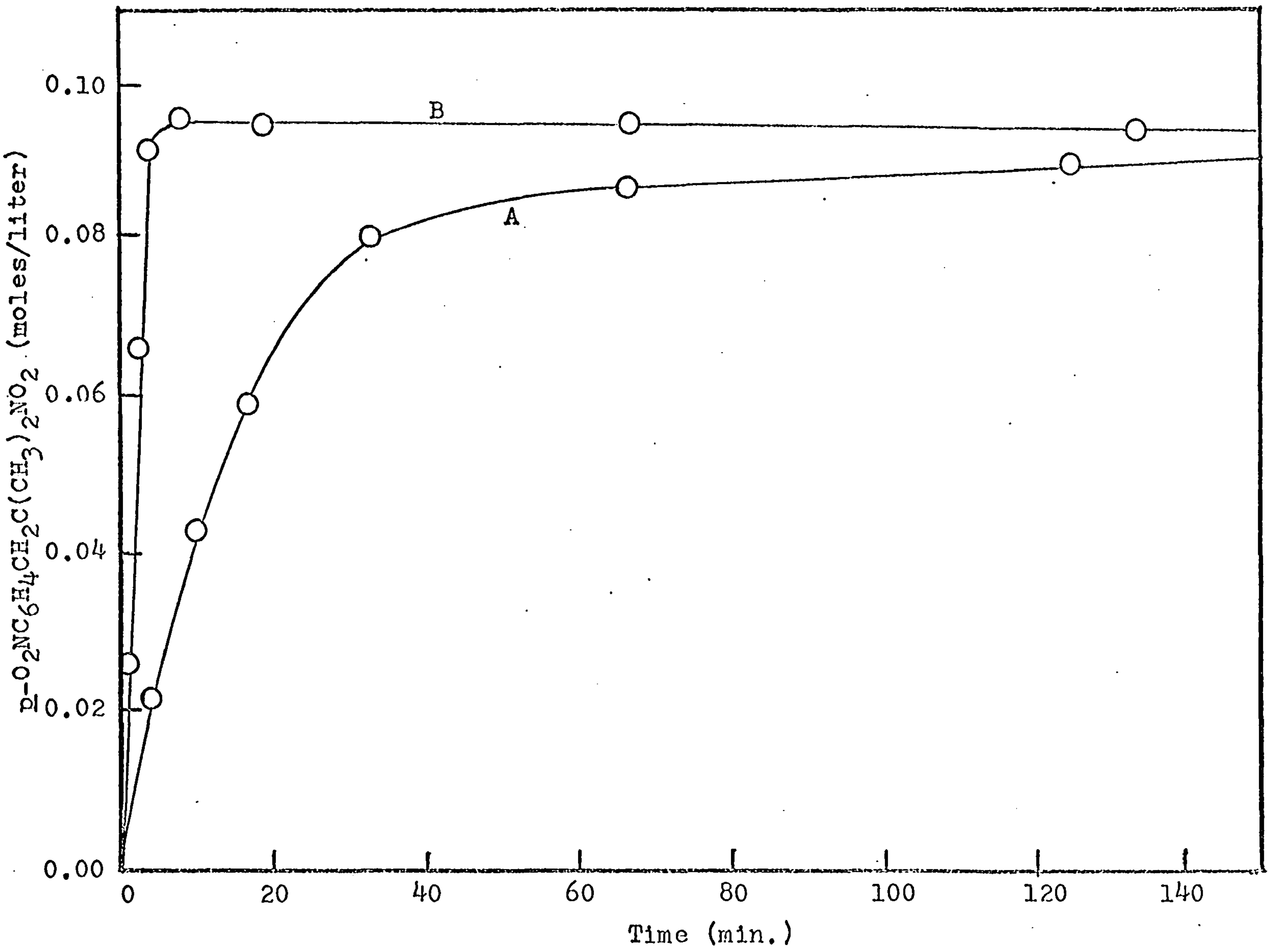

0.08
0.06
0.04
0.02
0.00
p-O$_2$NC$_6$H$_4$CH$_2$C(CH$_3$)$_2$NO$_2$ (moles/liter)
B
A
C
0
20
40
60
80
100
120
140
160
180
Time (min.)

Figure 15. Formation of coupled product in the reaction of 0.200 M lithium salt of 2-nitropropane with 0.100 M *p*-nitrobenzyl chloride under nitrogen in DMF at 0°C

A. Dark

B. Illuminated


B
A
p-$O_2NC_6H_4CH_2C(CH_3)_2NO_2$ (moles/liter)
0.10
0.08
0.06
0.04
0.02
0.00
0
20
40
60
80
100
120
140
Time (min.)

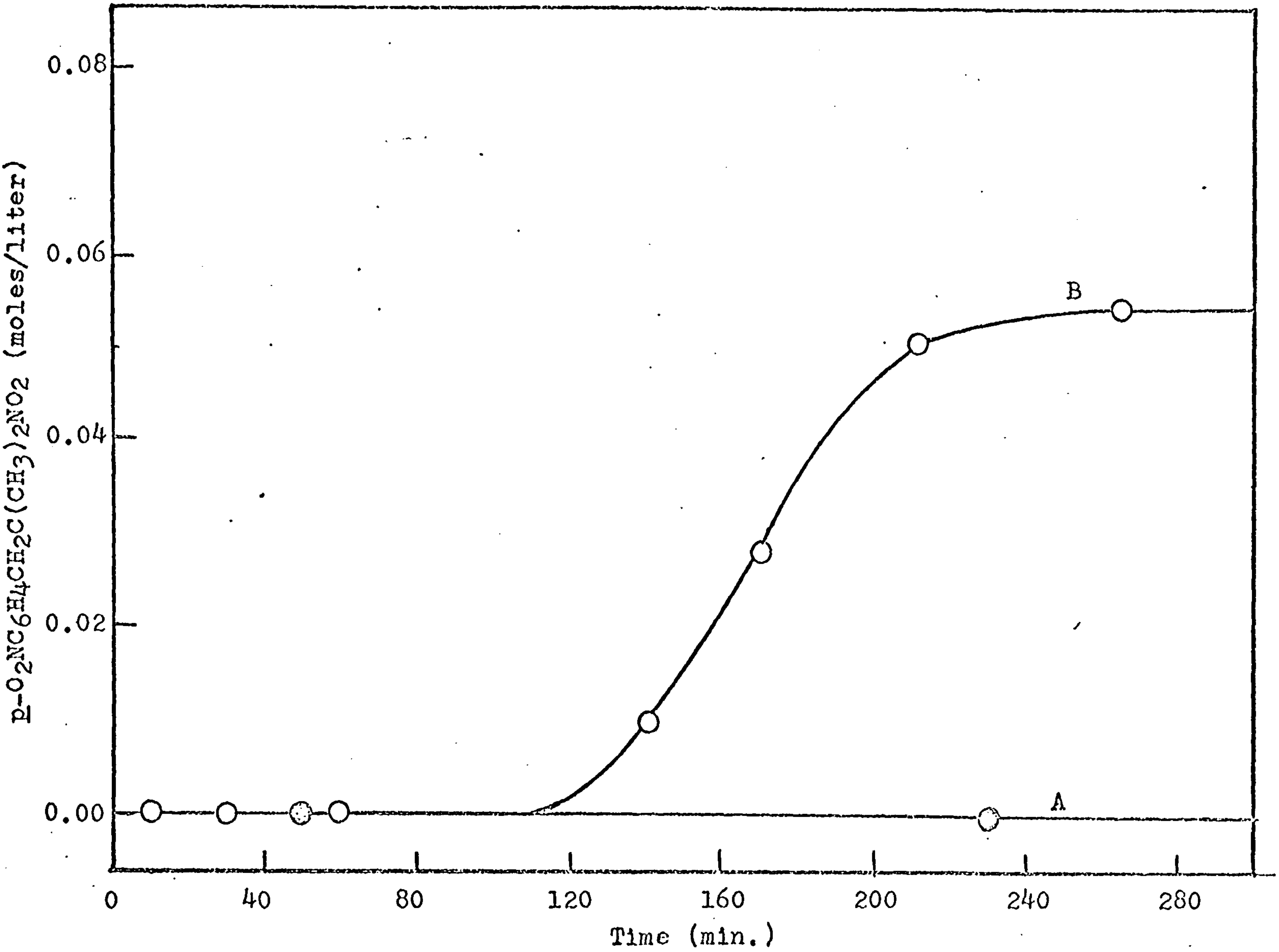
The effect of free radical inhibitors on the reaction in both DMF and ethanol was investigated. Figure 16 illustrates the effect of p-dinitrobenzene and hexaphenylethane on the yield of carbon alkylated coupled product formed in DMF in the dark and in the light respectively. A 20% amount of p-dinitrobenzene (based on concentration of p-nitrobenzyl chloride) will completely inhibit the formation of coupled product in the dark for periods of over 55 hours; 10% of hexaphenylethane will do likewise. It will be recalled that the formation of carbon alkylated product is essentially complete after approximately 1 hour in DMF in the dark (Figure 15). In light, 5.0% of hexaphenylethane will inhibit the formation of coupled product for approximately 2 hours (Figure 16). Without this trace amount of triphenylmethyl radicals present, a greater than 90% yield of carbon alkylated product is formed in less than 10 minutes. The fact that now only about 50% of coupled product is formed illustrates that oxygen alkylation is competing successfully to produce p-nitrobenzaldehyde. The effect of p-dinitrobenzene and hexaphenylethane on the reaction of p-nitrobenzyl chloride with the lithium salt of 2-nitropropane in ethanol was similar to that in DMF.

These results clearly demand a chain mechanism. Kornblum's explanation (27) for the effect of inhibitors (reactions 59 and 60) cannot account for the shape of the plotted line in Figure 16 for inhibition by hexaphenylethane

Figure 16. Formation of coupled product in the reaction of 0.200 M lithium salt of 2-nitropropane with 0.100 M p-nitrobenzyl chloride under nitrogen in DMF and dark at 0°C

A. In presence of 0.020 M p-dinitrobenzene

B. In presence of 0.005 M hexaphenylethane

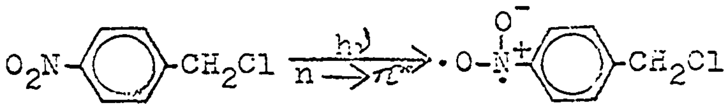

p-O2NC6H4CH2C(CH3)2NO2 (moles/liter)
0.08
0.06
0.04
0.02
0.00
B
A
0
40
80
120
160
200
240
280
Time (min.)

in the light. It is difficult to conceive how such a process can account for the complete suppression of formation of carbon alkylated product by such a small amount of inhibitor for such an extended period of time. The sigmoid shaped line is precisely that expected for an inhibited free radical chain mechanism. The inhibitor need only to intercept a few radical molecules to interrupt the chain process and such an interruption results in the non-formation of many molecules of product. Once the inhibitor is destroyed, reaction occurs rapidly as is demonstrated in Figures 11 and 16.

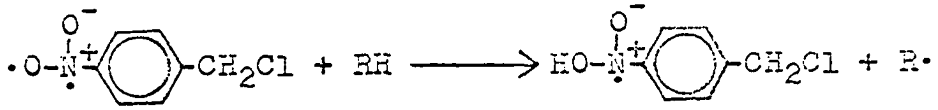
The reaction of m-nitrobenzyl chloride with the lithium salt of 2-nitropropane was also investigated to determine if carbon alkylation could be induced to occur when the reaction solution was irradiated. Under no conditions was any carbon-coupled product ever detected. In some cases, small amounts of 2,3-dimethyl-2,3-dinitrobutane were formed in the reaction. This could conceivably arise via a positive halogen process (39, 40).

The inability of m-nitrobenzyl chloride to produce carbon alkylated product by means of a free radical chain mechanism allows one to select between Scheme A and B (p. 37). All evidence (vide infra) supports Scheme B, the process involving a coupling of a radical with an anion. This mechanism for the 2-nitro-2-propyl anion--p-nitrobenzyl chloride system is illustrated in reactions 63-68:

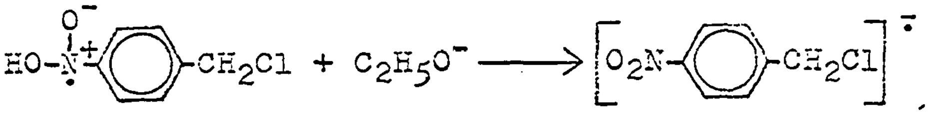
Initiation



(63)

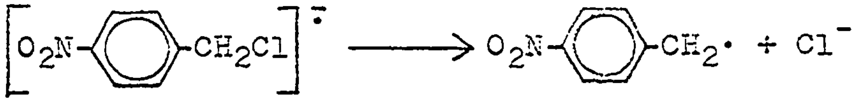


(64)

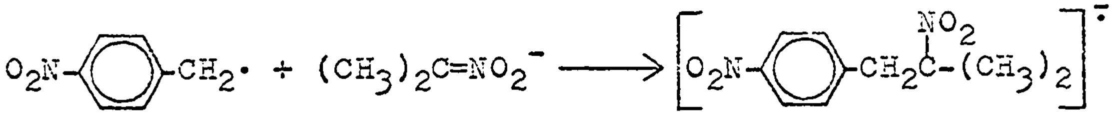


(65)

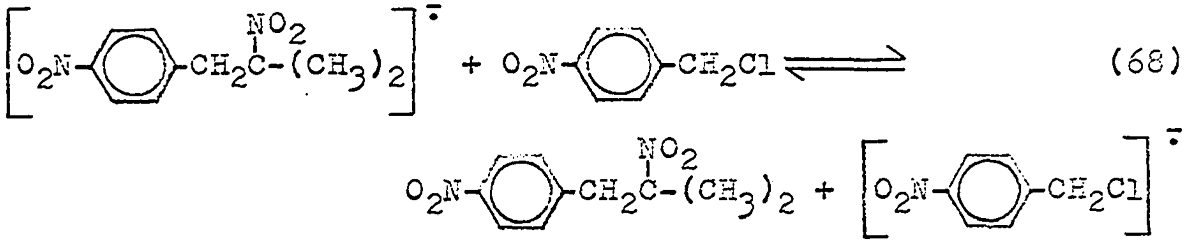
Propagation



(66)



(67)

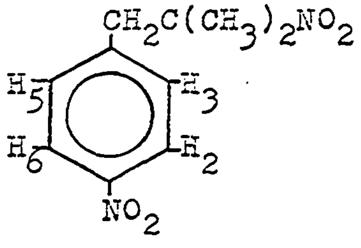


(68)

Here the initiation steps are postulated as occurring by means of a light-induced process eventually resulting in formation of the p-nitrobenzyl chloride radical anion. This process is the same as that discussed earlier for the case of the 2-halo-2-nitropropanes (reactions 24-27) and probably is an important source of p-nitrobenzyl radicals although other processes might also initiate the reaction.

p-Dinitrobenzene apparently exerts its quenching effect on the chain reaction by successfully competing with p-nitrobenzyl chloride in the electron transfer step of the propagation sequence (reaction 68). The *p*-dinitrobenzene radical anion thus formed transfers its electron to 2-nitro-2-propyl radical regenerating the inhibitor and forming a molecule of anion. The triphenylmethyl free radicals presumably intercept and couple with *p*-nitrobenzyl radicals and interrupt the chain process in this manner.

The low reactivity of *m*-nitrobenzyl chloride in the coupling reaction arises from the inability of the *m*-nitrobenzyl chloride radical anion to lose chloride ion to produce the *m*-nitrobenzyl free radical in a manner analogous to that of the *p*-nitrobenzyl chloride radical anion (reaction 66). The apparent explanation for this inability to undergo an internal loss of chloride ion is that given earlier (reactions 57 and 58). This conclusion receives support from electron spin resonance studies. When the photochemical coupling reaction of the 2-nitro-2-propyl anion with *p*-nitrobenzyl chloride is conducted in the spectrometer cavity, only the radical anion of the coupled product is observed (Figure 17). The spectrum is consistent with the following hyperfine splitting assignments:



$a^N = 12.73$ gauss
$a_{H_2}{}^H = a_{H_6}{}^H = 3.30$ gauss
$a_{H_3}{}^H = a_{H_5}{}^H = 1.12$ gauss
$a_{CH_2}{}^H = 1.845$ gauss

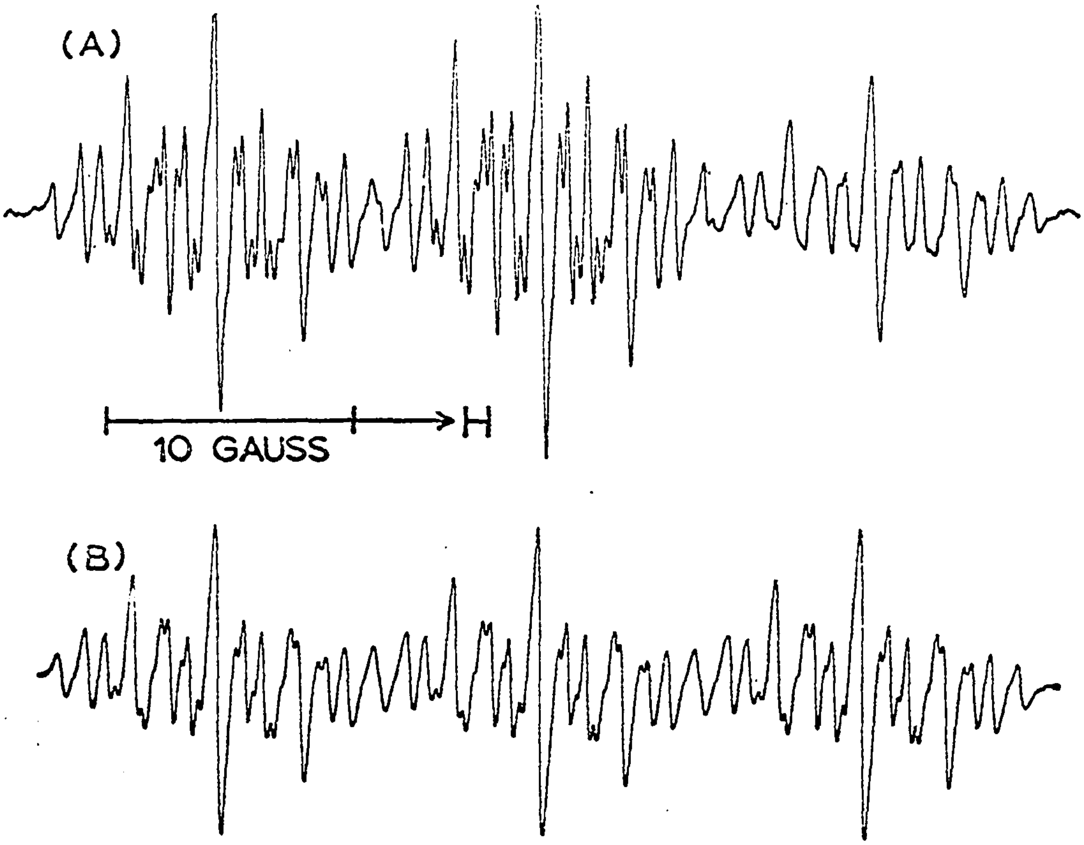


Figure 17. Electron spin resonance spectrum of the radical anion of the coupled product formed in the reaction of lithium salt of 2-nitropropane with p-nitrobenzyl chloride in ethanol with illumination

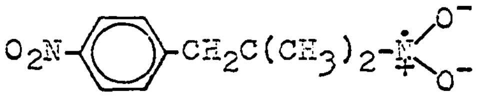
A. Experimentally obtained spectrum

B. Computer simulated; see text for assignments and values of hyperfine splitting constants

No signal is observed when p-nitrobenzyl chloride is irradiated in ethanol with lithium ethoxide, but a precipitate is formed in the cell which is presumably p,p'-dinitrostilbene (32).

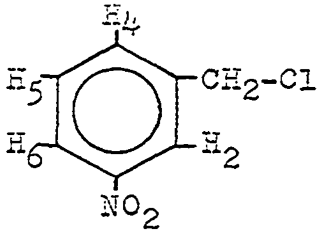
The p-nitrobenzyl chloride radical anion and the p-nitrobenzyl radical, formed in reactions 68 and 66 respectively, are not detected presumably because of their short lifetimes. The observed radical is also formed by the irradiation of the coupled product and the lithium salt of 2-nitropropane or lithium ethoxide; no signal is detected without light in ethanol solution. Thus, the detection of the radical anion does not constitute unequivocal evidence for reaction 67. It does, however, demonstrate the catalytic effect of light on electron transfer and lends support to the postulated initiation steps (reactions 63-65).

The initial product of reaction 67 might be expected to be



rather than the observed radical anion wherein the unpaired electron is delocalized throughout the π system. The radical anion initially formed could rapidly isomerize intramolecularly (33) to the observed radical anion or enter into reaction 68 prior to isomerization. Alternatively, reaction 68 could provide a mechanism for intermolecular isomerization of the radical anion of the coupled product.

When m-nitrobenzyl chloride and the lithium salt of 2-nitropropane are irradiated in ethanol in the cavity of the electron spin resonance spectrometer, the spectrum shown in Figure 18 is observed. This same spectrum is observed when m-nitrobenzyl chloride and lithium ethoxide are irradiated in ethanol; this demonstrates that the signal does not arise from the radical anion of the coupled product. It was also shown that the signal is not due to the radical anion of m-nitrobenzaldehyde. The spectrum apparently is that of the radical anion of m-nitrobenzyl chloride; a possible assignment of splitting constants is as follows:



$a^N = 12.93$ gauss

$a_{H_2}{}^H = a_{H_6}{}^H = 3.42$ gauss

$a_{H_4}{}^H = 3.58$ gauss

$a_{H_5}{}^H = a_{CH_2}{}^H = a^{Cl} = 0.57$ gauss

These results constitute direct proof of the instability of the radical anion derived from p-nitrobenzyl chloride as contrasted to that derived from m-nitrobenzyl chloride. The radical anion of the former has been observed by workers employing a flow technique (34). This work demonstrates that the m-nitrobenzyl chloride radical anion has considerable stability at room temperature and exhibits little tendency to eliminate chloride ion.

Such a finding clearly supports the chain mechanism in which the p-nitrobenzyl radical couples with the

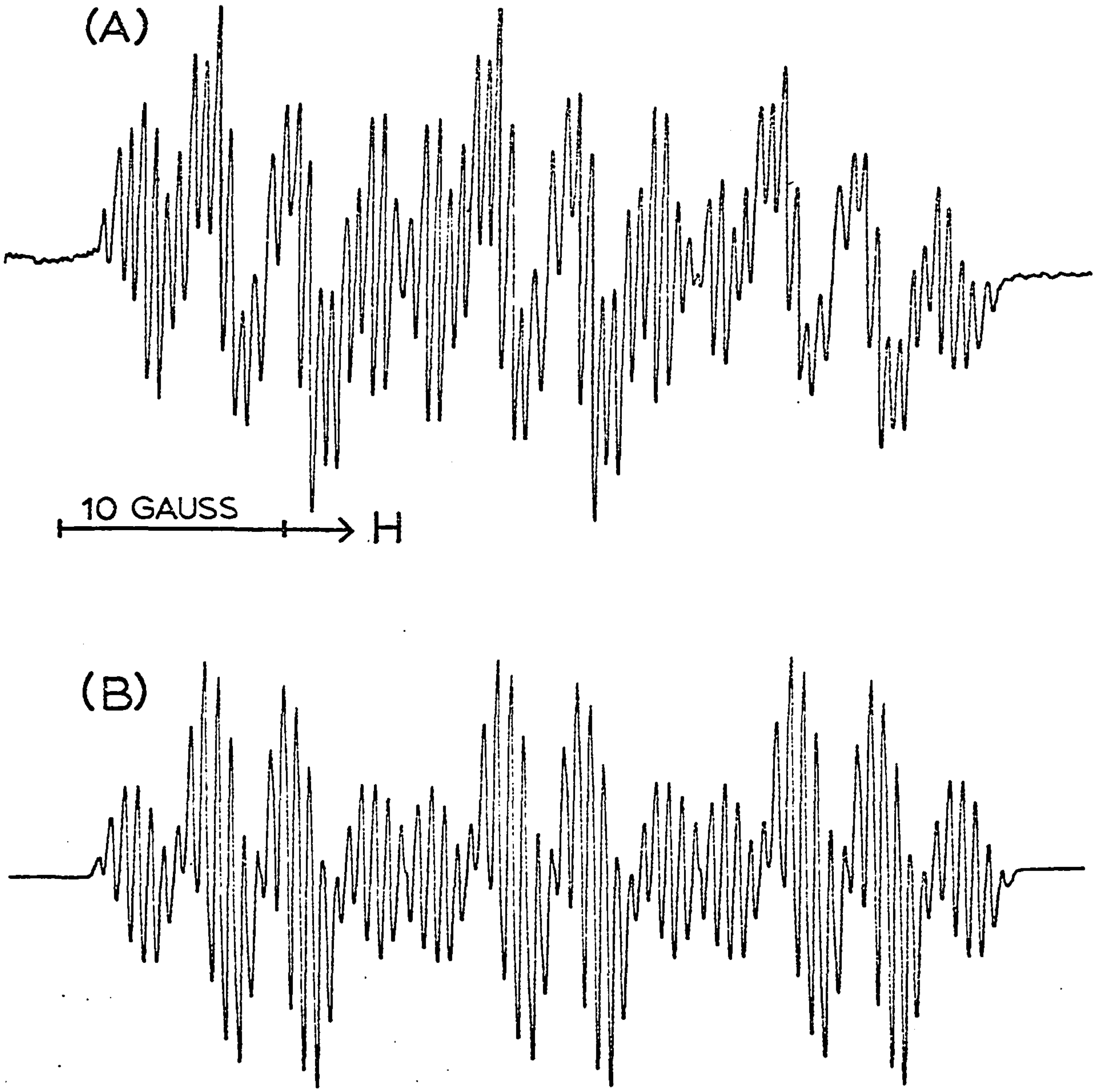


Figure 18. Electron spin resonance spectrum of the radical anion derived from irradiation of *m*-nitrobenzyl chloride in the presence of lithium ethoxide in ethanol

A. Experimentally obtained spectrum

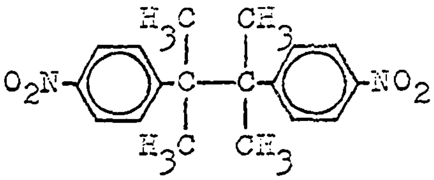
B. Computer simulated spectrum; see text for assignments and values of hyperfine splitting constants

2-nitro-2-propyl anion for a key step in the propagation of the chain demands that the radical anion of the chloro compound be unstable with respect to elimination of chloride ion (reaction 66). The stability of the m-nitrobenzyl chloride radical anion prevents this elimination and does not permit the radical chain mechanism to compete with the simultaneous S_N2 reaction producing oxygen alkylation.

A radical displacement on carbon process (Scheme A, p. 37) is also eliminated as a mechanistic possibility by an experiment in which excess lithium salt of 2-nitropropane is allowed to react with an equimolar mixture of m- and p-nitrobenzyl chloride. The para isomer reacts rapidly to give carbon coupled product while the meta compound is not consumed. It appears highly unlikely that if the 2-nitro-2-propyl radical is displacing a chlorine atom from a benzylic carbon, that the positioning of the nitro substituent meta or para to the benzyl group should alter the course of the reaction so drastically.

A communication describing the above results was published at this point (35). Submission of the paper for publication was withheld until Kornblum, et al. completed work necessary for a simultaneous publication (36, 37). In these works Kornblum also concludes that the reaction of p-nitrobenzyl chloride with the lithium salt of 2-nitropropane is a free radical chain process involving the coupling of the p-nitrobenzyl radical with the anion; this work refutes his earlier proposed mechanism (27). His conclusion is based mainly on the inhibitory effect of small amounts of cupric chloride on the reaction. Inhibition apparently results from ligand transfer oxidation of the p-nitrobenzyl radical by cupric chloride thus interrupting the chain process.

In a later communication Kornblum, et al. published the results of the reaction of p-nitrocumyl chloride with various anions (sodium thiophenoxide, lithium salt of 2-nitropropane, malonyl ester anions, and sodium salt of 1-methyl-2-naphthol) and explained the facile substitution of the tertiary chloro compound as a result of the radical chain mechanism (38). The compound



is isolated in 1-5% yields, but such an observation does not necessarily prove that this compound is formed by simple dimerization of p-nitrocumyl radicals. A more likely explanation is that the p-nitrocumyl chloride undergoes a positive halogen reaction (39, 40) with an anion to produce the p-nitrocumyl anion which can then couple with the p-nitrocumyl radical to produce the radical anion of the dimer.

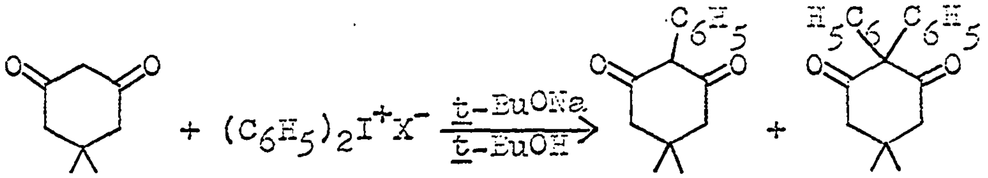
C. Reaction of 2-Phenyl-1,3-indandione with Diphenyliodonium Salts

1. Literature review

Many organic and inorganic anions react with diphenyliodonium cation to give phenylated products and iodobenzene (41, 42):

$$(C_6H_5)_2I^+ + R^- \longrightarrow C_6H_5R + C_6H_5I \qquad (69)$$

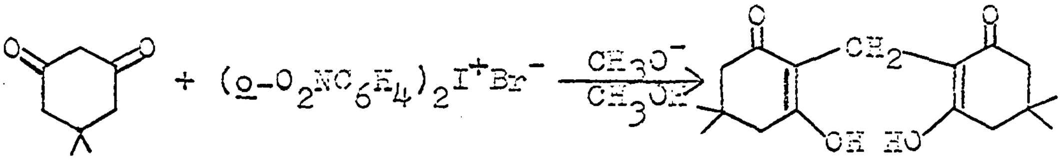
The first evidence that free radicals are formed as intermediates in the phenylation of carbanions was obtained in the reaction of dimedone (5,5-dimethylcyclohexane-1,3-dione) with diphenyliodonium chloride (42). In *t*-butyl alcohol at reflux temperature dimedone is converted by sodium *t*-butoxide and diphenyliodonium chloride or tosylate into 2-phenyldimedone and 2,2-diphenyldimedone:



(70)

In water 2,2-diphenyldimedone was obtained but no monophenylated product could be isolated. It was shown that 2-phenyldimedone could be converted under the first conditions to 2,2-diphenyldimedone. When di-(*o*-nitrophenyl)iodonium bromide replaced diphenyliodonium chloride in the reaction, similar results were obtained except that no diphenylated product was isolated.

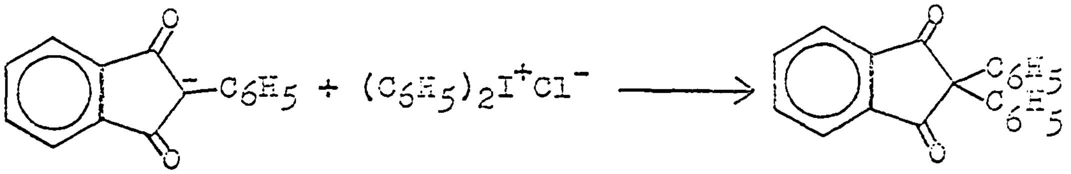
The replacement of t-butyl alcohol by methanol or ethanol brought about a complete change in the nature of the main products. The reaction of di-(o-nitrophenyl)iodonium bromide in methanol produced 2,2-methylene-bis-dimedone as the only isolable product in 66% yield:



(71)

With diphenyliodonium chloride in ethanol a complex mixture was formed from which 2-phenyl- and 2,2-diphenyldimedone and 2,2'-ethylidene-bis-dimedone were all isolated in low yields. These results indicate that the alcohol apparently is dehydrogenated to the corresponding aldehyde which then condensed with the dimedone (43). Such a dehydrogenation suggests the intermediacy of free radicals in the reaction.

A study of the mechanism of the phenylation reaction was conducted by Beringer, et al. in 1962 (44). A solution containing the sodium salt of 2-phenyl-1,3-indandione and an equivalent of diphenyliodonium chloride in refluxing t-butyl alcohol gave as the major product (86% yield) 2,2-diphenyl-1,3-indandione:


(72)

Other products were iodobenzene, biphenyl, and a small amount of a compound believed to be that formed by coupling of two 2-phenyl-1,3-indandion-2-yl free radicals although the structure has not been definitely assigned. When diphenyliodonium acetate was used in place of diphenyliodonium chloride in the phenylation, the reaction time was reduced from six hours to one hour and the yield of 2,2-diphenyl-1,3-indandione was increased from 86% to 93%.

That free radicals are intermediates in the phenylation of 2-phenyl-1,3-indandione was suggested by the observation that isopropyl alcohol is dehydrogenated to acetone with concomitant formation of benzene when this alcohol is present in the reaction; this result parallels the behavior of methanol and ethanol in the attempted phenylation of dimedone (42). The yield of 2,2-diphenyl-1,3-indandione fell to 49% when isopropyl alcohol was present. These observations were rationalized by assuming the intermediacy of phenyl free radicals and led to the addition of radical scavengers to the phenylation reaction. When styrene was added to a solution of the anion of 2-phenyl-1,3-indandione and diphenyliodonium chloride in *t*-butyl alcohol, a decreased yield (70%) of phenylated product was obtained along with low polymers of styrene; no polystyrene was formed in the reaction mixtures from which diphenyliodonium chloride was omitted. This result was rationalized by assuming that the anion was oxidized to the 2-phenyl-1,3-indandion-2-yl free radical which initiated polymerization of styrene. It was also shown that although oxygen does not oxidize the anion of 2-phenyl-1,3-indandione at 80° C, oxygen bubbled through a refluxing solution of the carbanion and diphenyliodonium chloride in *t*-butyl alcohol reduced the yield of phenylated product to 53%.

The above observations prompted the following general mechanism for phenylation reactions involving a carbanion (R^-) and an iodonium salt ($Ar\overset{+}{I}Ar$) (44):

$$Ar\overset{+}{I}Ar + R^- \rightleftharpoons \underset{\text{ion pair}}{Ar\overset{+}{I}ArR^-} \qquad (73)$$

$$\underset{\text{ion pair}}{Ar\overset{+}{I}ArR^-} \rightleftharpoons \underset{\text{radical pair}}{Ar\overset{\bullet}{I}ArR\cdot} \qquad (74)$$

$$\underset{\text{radical pair}}{Ar\overset{\bullet}{I}ArR\cdot} \longrightarrow ArR + ArI \qquad (75)$$

$$\underset{\text{radical pair}}{Ar\overset{\bullet}{I}ArR\cdot} \longrightarrow \underset{\text{radical pair}}{Ar\cdot R\cdot} + ArI \qquad (76)$$

$$\underset{\text{radical pair}}{Ar\cdot R\cdot} \longrightarrow ArR \qquad (77)$$

$$\underset{\text{radical pair}}{Ar\cdot R\cdot} \longrightarrow \underset{\text{free radicals}}{Ar\cdot + R\cdot} \qquad (78)$$

$$\underset{\text{free radicals}}{Ar\cdot + R\cdot} \longrightarrow Ar\text{-}R + Ar\text{-}Ar + R\text{-}R \qquad (79)$$

<u>Overall reaction</u>

$$Ar\overset{+}{I}Ar + R^- \longrightarrow ArR + ArI + ArAr + RR \qquad (80)$$

It was proposed that in _t_-butyl alcohol the carbanion and iodonium ion exist largely as ion pairs (reaction 73) and that electron transfer within this ion pair gives a radical pair (reaction 74). The members of such radical pairs in _t_-butyl alcohol largely react together, either by radical displacement of R· on diphenyliodine (reaction 75) or by coupling of R· and phenyl radicals (reactions 76 and 77). Some free radicals are formed by diffusing apart of the radical pairs (reaction 78) which later couple to give ArR, ArAr, and RR (reaction 79).

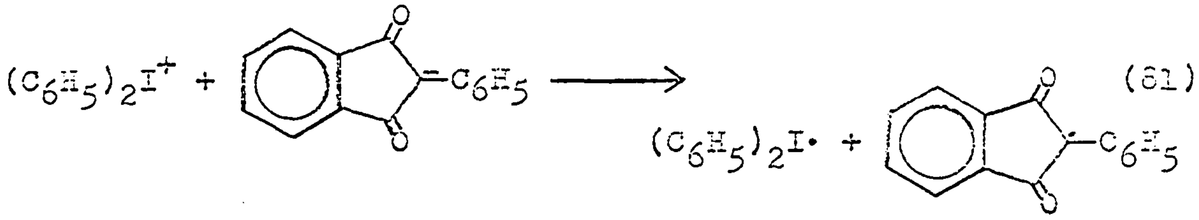
Evidence for the electron transfer from carbanion to iodonium salt to give a radical pair (reaction 74) receives support from electroreduction studies by Beringer, _et al_. (45, 46) who showed that diphenyl iodonium salts undergo a facile one electron reduction to diphenyliodine. Diphenyliodine has also been postulated as a reaction intermediate (47).

Since the yield of phenylated product (ArR) can be as high as 93%, it seems that if the above mechanism is correct, most of the yield of ArR is accounted for by reaction within the radical pair, and only a small amount arises from recombination of free radicals. Since the presence of isopropyl alcohol, styrene, or oxygen depresses the yield of ArR to 70% or below, Beringer, _et al_. (44) conclude that these reagents must be somewhat reactive to radical pairs as well as to free radicals.

2. Results and discussion

The reaction of the 2-phenyl-1,3-indandione anion with diphenyliodonium tosylate was investigated to determine if this reaction might also be a free radical chain process involving a coupling between a phenyl radical and carbanion:

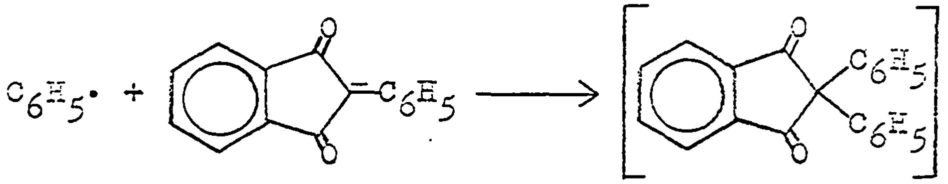
Initiation



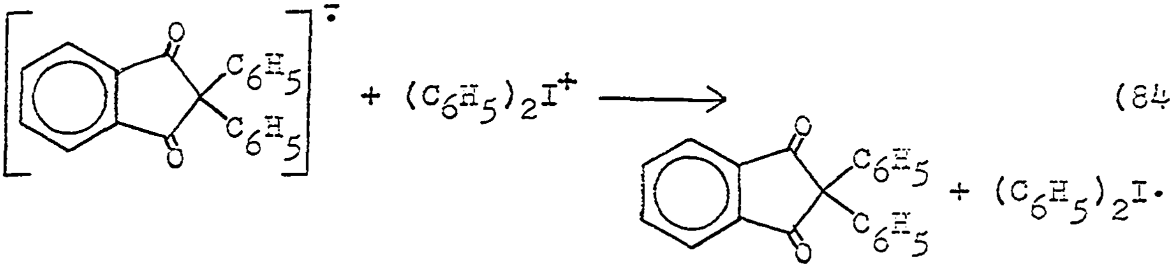
(81)

Propagation

$$(C_6H_5)_2I\cdot \longrightarrow C_6H_5I + C_6H_5\cdot \qquad (82)$$



(83)



(84)

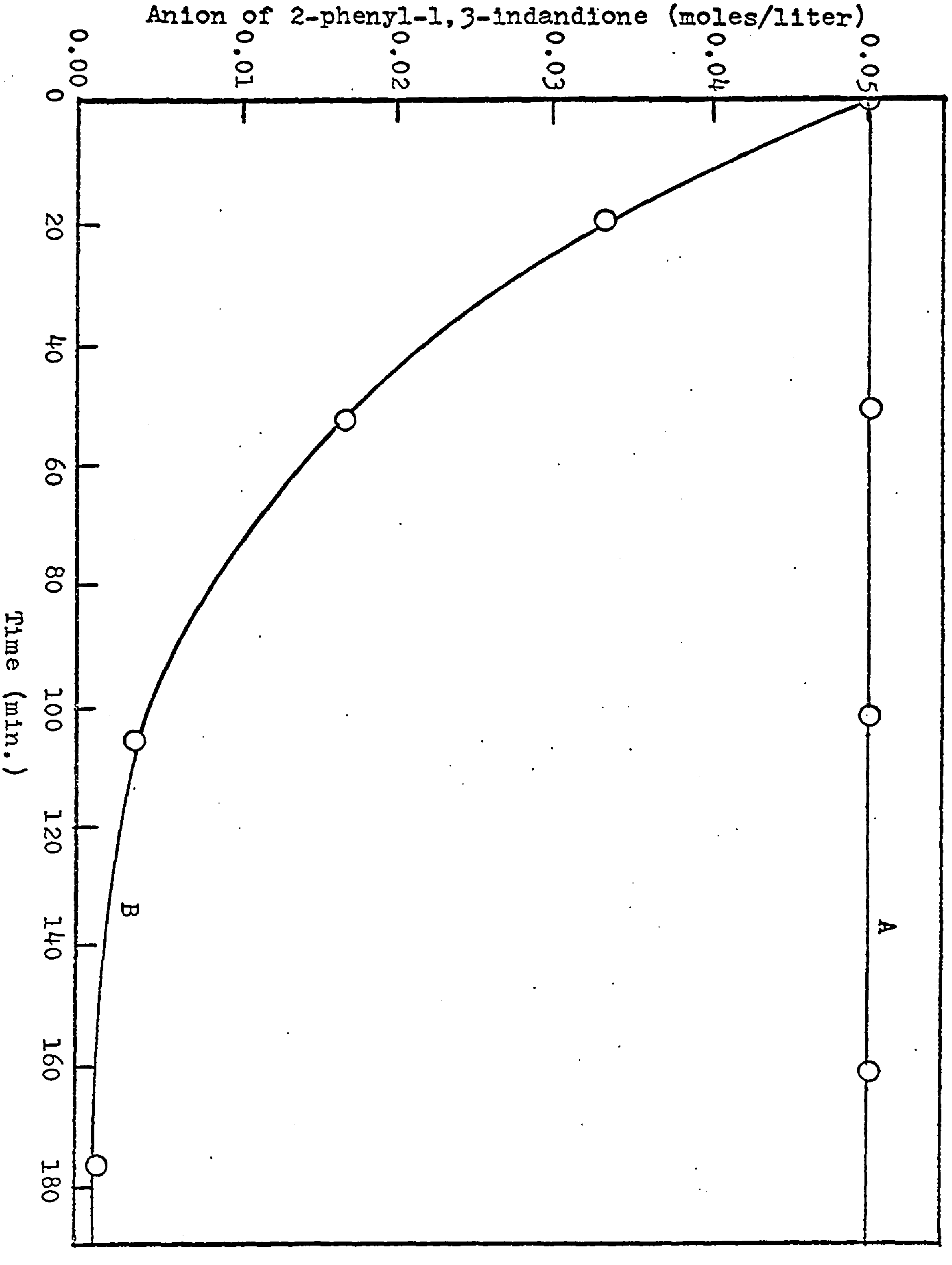
The reaction was conducted in ethyl alcohol at 30°C, the same conditions as previous work discussed in this thesis. The change in concentration of 2-phenyl-1,3-indandione anion was monitored during the course of the reaction by noting the absorption spectrum of the anion which has a maximum at 4520 Å. In the dark, 42% of the anion is consumed after a reaction time of 7.7 hours; 63% of the anion had reacted after 23 hours. When the reaction is conducted under irradiation from a sunlamp a somewhat different behavior is observed. After a reaction time of only 43 minutes 24% of the anion is consumed. However, continued irradiation produces only a small change in the concentration of anion; after reaction for 23 hours only 28% of the anion is consumed. Apparently light decomposes the iodonium compound (48) which then reacts with the solvent quite rapidly resulting in only a small amount of the anion being consumed. In the dark, reaction is much slower and more selective, possibly proceeding via an ion pair between the anion and iodonium compound which would result in the consumption of more anion. The use of ethanol for this reaction reflects the difficulties encountered with this solvent in the attempted phenylation of dimedone with diphenyliodonium chloride (42).

When DMF was employed as solvent completely different results were obtained. Figure 19 demonstrates that virtually all of the 2-phenyl-1,3-indandione anion is consumed after a reaction time of approximately 2 hours when the reaction is irradiated; no reaction occurs in the dark in this solvent. The catalytic effect of light on the rate of the reaction parallels its influence on the rate of reaction of the lithium

Figure 19. Reaction of 0.050 M 2-phenyl-1,3-indandione and 0.075 M potassium t-butoxide with 0.055 M diphenyliodonium tosylate under nitrogen in DMF at 30° C

A. Dark

B. Illuminated


Anion of 2-phenyl-1,3-indandione (moles/liter)
0.00
0.01
0.02
0.03
0.04
0.05
Time (min.)
0
20
40
60
80
100
120
140
160
180
A
B

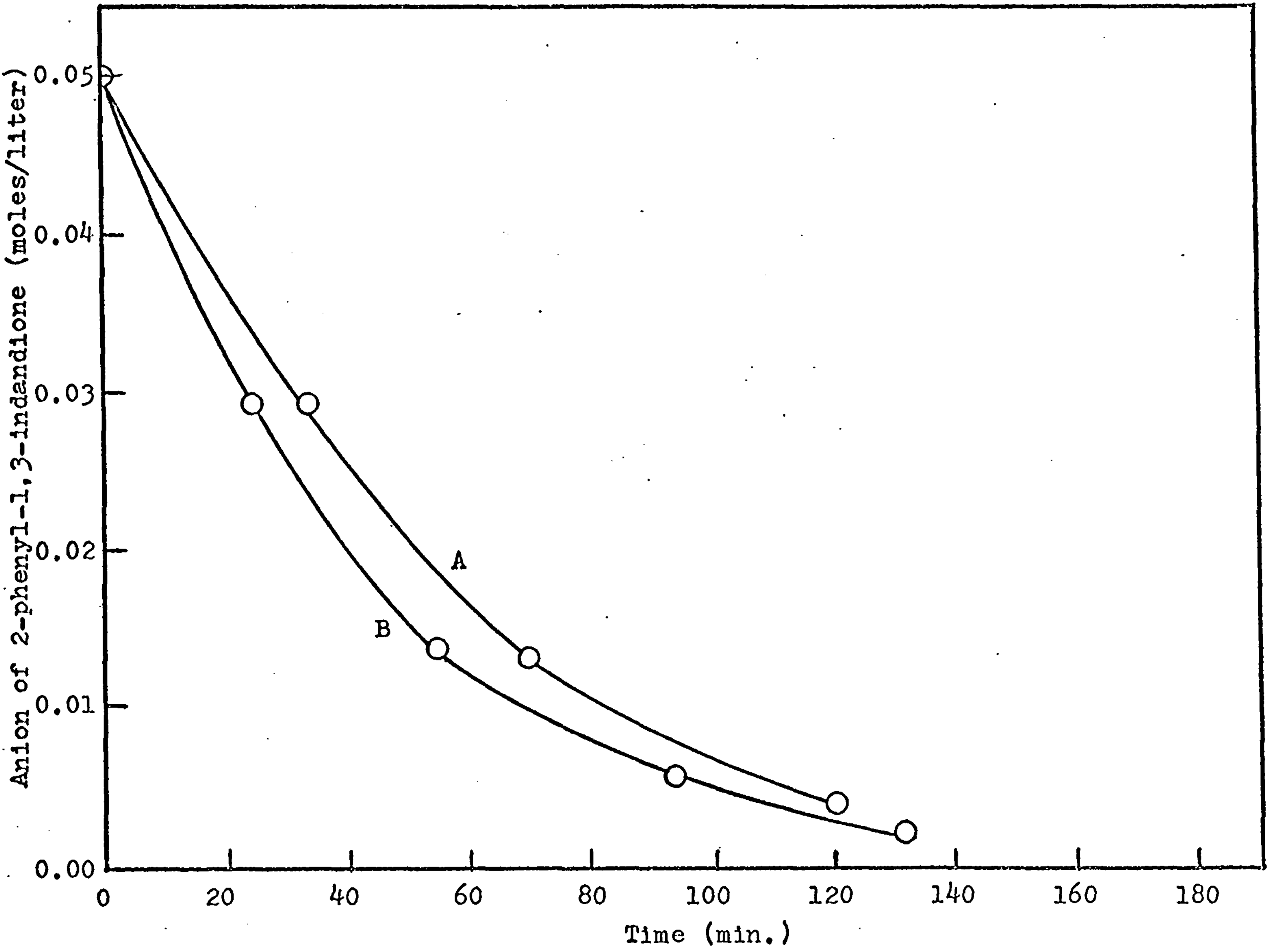
salt of 2-nitropropane with 2-halo-2-nitropropane and p-nitrobenzyl chloride as discussed earlier.

Following the usual technique of determining the effect of oxygen on the course of the reaction it was shown that oxygen does not react with the potassium salt of 2-phenyl-1,3-indandione in DMF. Even after shaking in the presence of oxygen for 18 hours no decrease in the concentration of anion is observed and no oxygen absorption is detected. In an attempt to inhibit the reaction of the anion with diphenyliodonium tosylate with oxygen it is noted that, although a small amount of oxygen is taken up during the reaction, the rate of disappearance of the 2-phenyl-1,3-indandione anion is virtually the same as when the reaction is conducted in an inert atmosphere of nitrogen (Figure 20). Approximately 0.27 mmoles of oxygen is absorbed during the course of the reaction which involves 1.00 mmole of anion and 1.10 mmoles of diphenyliodonium tosylate. However, the error in measuring the amount of oxygen consumed in this reaction is probably quite large due to variations in the temperature of the reaction flask and surrounding atmosphere including the burets holding the oxygen due to the proximity of the sunlamp. Virtually all the anion is consumed in the reaction (Figure 20) and little if any inhibitory effect on the rate of disappearence of anion is observed. These results seem to indicate that oxygen has little effect on the reaction. It will be recalled that Beringer detected a decrease in yield of phenylated product

Figure 20. Reaction of 0.050 M 2-phenyl-1,3-indandione with 0.075 M potassium *t*-butoxide with 0.055 M diphenyliodonium tosylate in DMF at 30°C

A. Illuminated in presence of oxygen

B. Illuminated under nitrogen and in presence of 0.0024 M *p*-dinitrobenzene



Anion of 2-phenyl-1,3-indandione (moles/liter)
0.05
0.04
0.03
0.02
0.01
0.00
0
20
40
60
80
100
120
140
160
180
Time (min.)
A
B

from 86% to 53% when oxygen was bubbled through the refluxing reaction solution (44), but in this reaction t-butyl alcohol was employed as solvent.

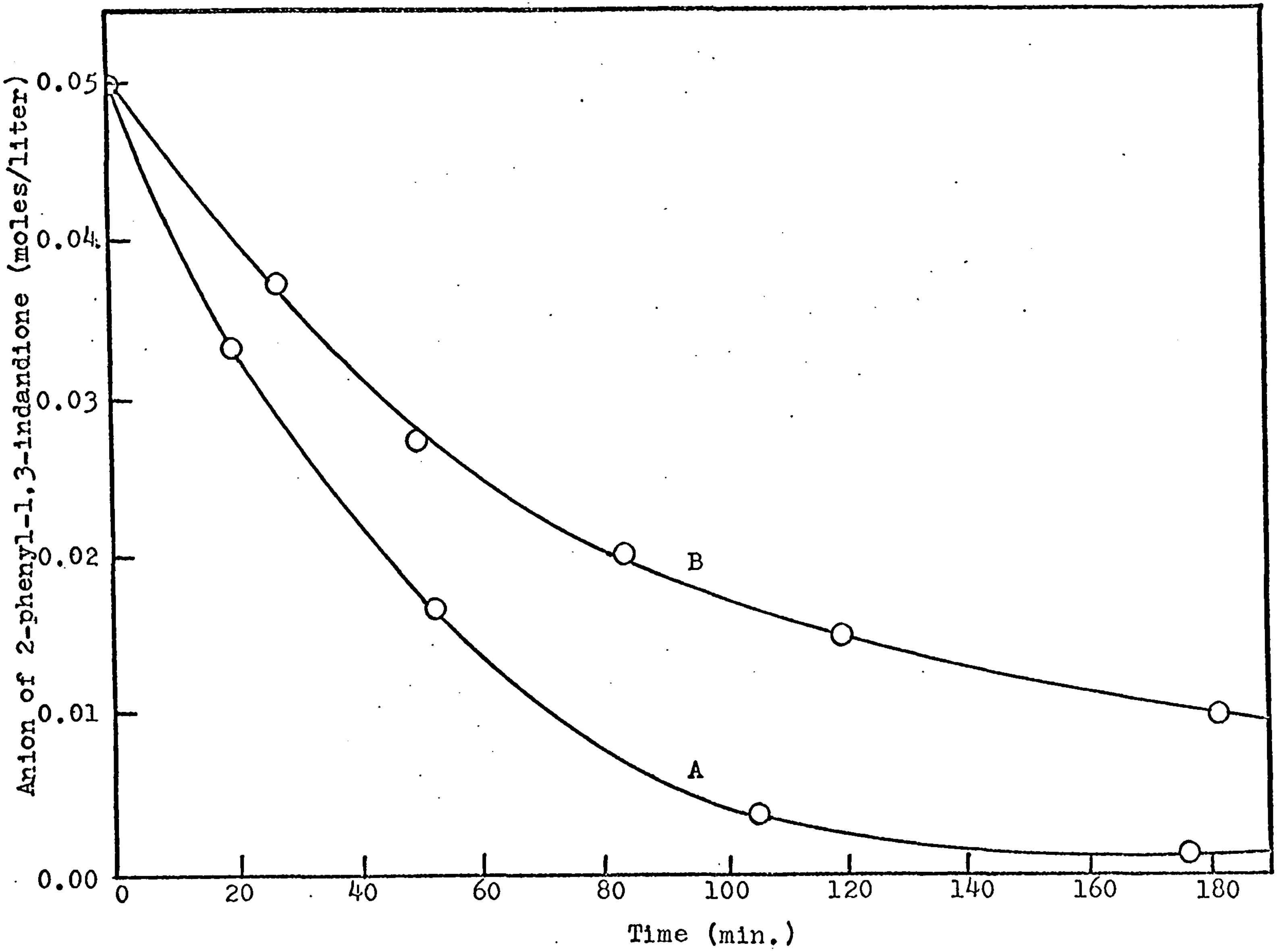
Attempting to inhibit the reaction with 4.8% of p-dinitrobenzene likewise failed to produce any significant decrease in the rate of reaction of the anion. However, a small effect is noted when 5.0% of hexaphenylethane is introduced into the reaction (Figure 21). But the inhibition is not nearly as pronounced as noted in earlier work. Thus, the free radical inhibitors which are so effective in quenching the reaction of the lithium salt of 2-nitropropane with 2-halo-2-nitropropane and p-nitrobenzyl chloride have little effect on the reaction of the anion derived from 2-phenyl-1,3-indandione with diphenyliodonium tosylate.

The inability of oxygen and p-dinitrobenzene to inhibit the reaction, if indeed a free radical chain mechanism is operative, may be due to the differences in reduction potentials of these two compounds versus that of the diphenyliodonium salt. The very low reduction potential of diphenyliodonium salts (-0.19 v. referred to the saturated calomel electrode for diphenyliodonium chloride--45, 46) may cause the electron transfer from the 2,2-diphenyl-1,3-indandione radical anion to the iodonium salt (reaction 84) to occur so rapidly and facilely that oxygen and p-dinitrobenzene are unable to compete for the electron and inhibit the chain process as discussed earlier for the p-nitrobenzyl chloride

Figure 21. Reaction of 0.050 M 2-phenyl-1,3-indandione and 0.075 M potassium _t_-butoxide with 0.055 M diphenyliodonium tosylate under nitrogen in DMF at 30° C

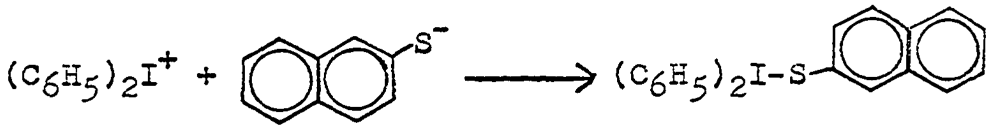
A. Illuminated

B. Illuminated in presence of 0.0025 M hexaphenylethane


Anion of 2-phenyl-1,3-indandione (moles/liter)
0.05
0.04
0.03
0.02
0.01
0.00
0
20
40
60
80
100
120
140
160
180
Time (min.)
A
B

system. But, unless the reaction of phenyl radicals with 2-phenyl-1,3-indandione anions is extremely rapid, inhibition by triphenylmethyl radicals should occur since this radical should intercept the phenyl radicals and interrupt the chain process. Since the addition of hexaphenylethane to the reaction solution does have a small effect on the rate of anion consumption, it can perhaps be optimistically concluded that the phenylation reaction proceeds at least in part via a chain mechanism such as that postulated in reactions 81-84.

Beringer, _et_ _al_. (44) have reported that substituting diphenyliodonium acetate for diphenyliodonium chloride in the reaction with the anion of 2-phenyl-1,3-indandione results in a slightly greater yield of phenylated product in much shorter reaction times. This experiment was repeated with the following observations. Although 2-phenyl-1,3-indandione (not the anion) and diphenyliodonium acetate by themselves are both colorless and soluble in _t_-butyl alcohol, a deep red precipitate develops immediately upon mixing the two solutions at 30°C. In an attempt to bring this precipitate back into solution the reaction temperature was raised to 50°C. Although this does not dissolve the precipitate, it is noted that after approximately one hour no precipitate or color remains and analysis of the reaction solution, after the addition of base, indicates no 2-phenyl-1,3-indandione anion is present. Apparently the acetate anion removes the proton from 2-phenyl-1,3-indandione ($pK_a = 4.4$ in 50% ethanol-water--44) and the ion pair thus formed precipitates from solution and slowly reacts. This phenomenon possibly lends support to Beringer's mechanism for the phenylation reaction wherein both ion pairs and radical pairs are postulated (44). No precipitates are mentioned, however, in the reactions of 1,3-indandione and substituted 1,3-indandiones with diphenyliodonium salts, although it is known that transient yellow colors or unstable yellow to orange precipitates are formed when an iodonium halide is added to a strong nucleophile such as an organometallic compound or the sulfide ion (49, 50). Greidanus, <u>et al</u>. have reported the preparation of stable yellow compounds from iodonium salts and the anion of 2-naphthalenethiol and the anions of several diketones (51):



(86)

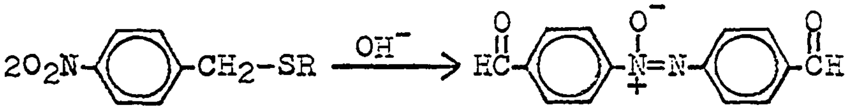
When this compound is heated in cyclohexane or exposed in carbon tetrachloride to sunlight or ultraviolet light for 48 hours, decomposition occurs to iodo compounds and free radicals which react with each other and with the solvent.

The fact that such trisubstituted iodine compounds have been isolated lends support to Beringer's published mechanism for the reaction of anions with iodonium salts (reactions 73-80) (44); the ion pair initially formed could instead conceivably be a trisubstituted iodine compound. Such a change in covalency would not alter the validity of subsequent reactions. Thus, inspite of the catalytic effect of light and the slight inhibitory effect of hexaphenylethane on the reaction of the anion of 2-phenyl-1,3-indandione with diphenyliodonium tosylate, it appears that the process is not a free radical chain mechanism.

D. Reaction of *p*-Nitrobenzylsulfonium Salts with Hydroxide and 2-Nitro-2-propyl Anions

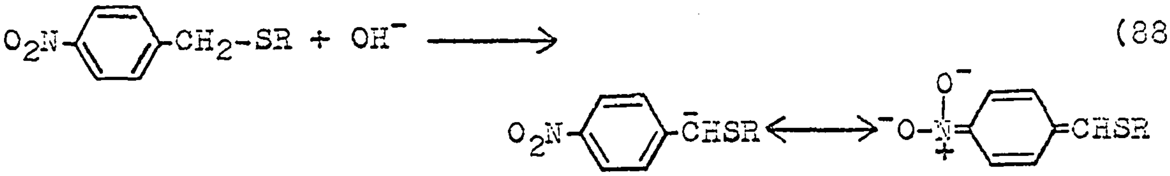
1. Literature review

The product resulting from the reaction of various *p*-nitrobenzyl compounds with aqueous alkaline solutions depends very critically upon the leaving group. Iskander and Riad have shown that the alkaline hydrolysis of *p*-nitrobenzylthioacetic acid and other *p*-nitrobenzylthio acids results in the formation of *p*-azoxybenzaldehyde (52, 53):



(87)

The *m*-nitrobenzylthio acids were recovered completely unchanged from the alkaline solutions after refluxing 15 minutes; the *o*- and *p*-nitro compounds were rapidly and completely hydrolyzed even in the cold. The following mechanism was postulated for the formation of *p*-azoxybenzaldehyde: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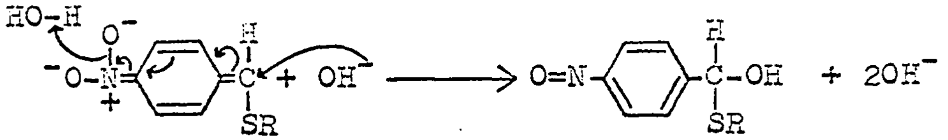
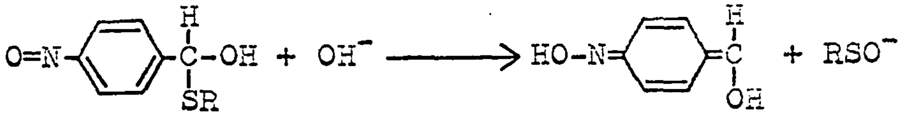

(89)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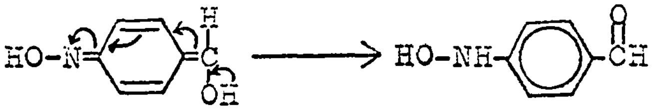
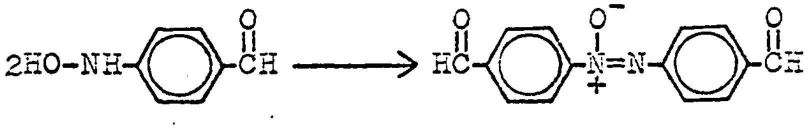
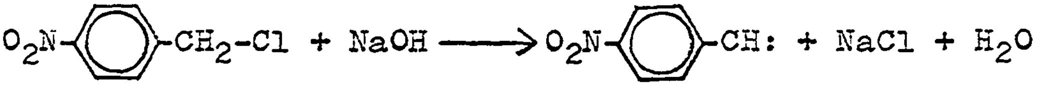
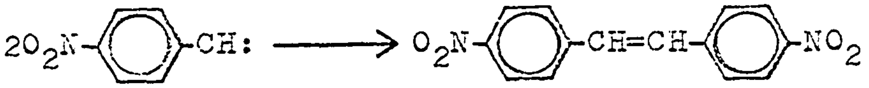

(91)


(92)

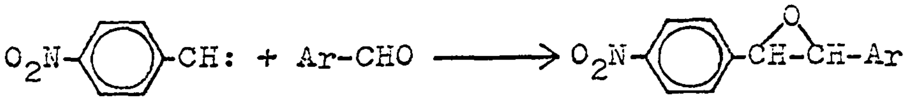
More recently Hanna has investigated the reaction of *p*-nitrobenzylpyridinium chloride and bromide in aqueous alkaline solution and has shown that the product is also *p*-azoxybenzaldehyde (54).

A completely different product is obtained when *p*-nitrobenzyl chloride is reactant. When this compound is hydrolyzed by alkali in water, it gives the expect *p*-nitrobenzyl alcohol (55); reaction in aqueous alcohol, acetone, or dioxane gives *p,p*'-dinitrostilbene (56). This abnormal behavior was investigated by Bergmann and Hervey (57) who proposed a mechanism involving *p*-nitrophenylcarbene:


(93)

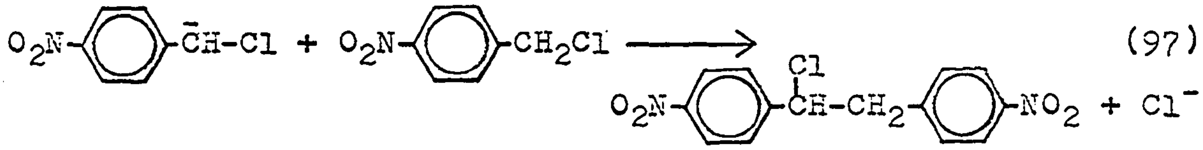

(94)

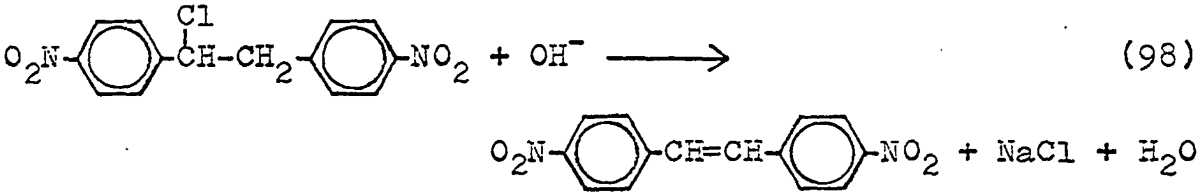
They based their proposal on the fact that in the presence of carbonyl compounds the reaction would be diverted to the formation of epoxides:


(95)

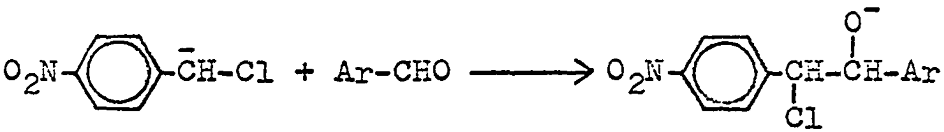
Hahn (58) and Kleucker (59), on the other hand, considered that the reaction involved nucleophilic displacement by a carbanion:

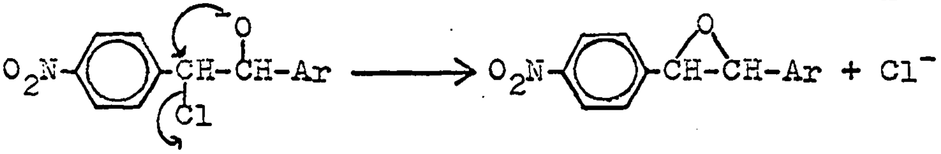

(96)


(97)


(98)

In this case the intercepting process would be:

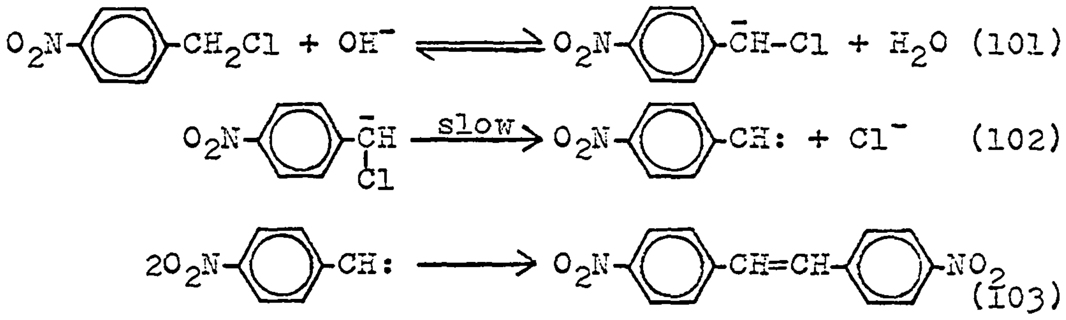

(99)


(100)

A kinetic investigation of this reaction was reported in 1961 (60, 61) which showed that the reaction is second order:

$$\frac{d\left[Cl^-\right]}{dt} = k_2\left[\underline{p}\text{-}O_2NC_6H_4CH_2Cl\right]\left[OH^-\right]$$

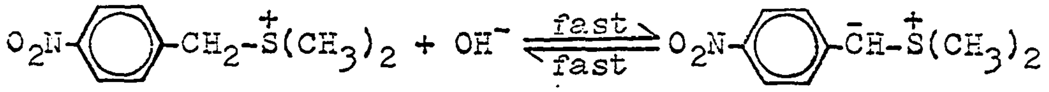
The considerable reactivity of p-nitrobenzyl chloride relative to other substituted benzyl chlorides suggests that the first stage in its reaction with alkali is removal of a proton which these workers demonstrated to be reversible since p-nitrobenzyl chloride recovered after partial reaction in dioxane-D_2O contained deuterium. These results indicate that neither reaction 96 nor 97 of Hahn's mechanism is rate determining. The following modification of earlier mechanisms, designated α-Elcb, was proposed:



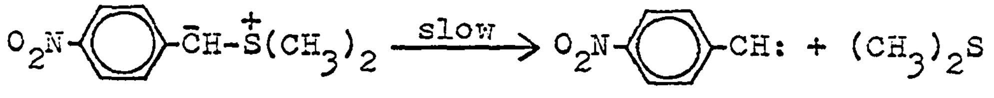
p-Nitrobenzaldehyde diverts the reaction to form an epoxide with an increase in the rate of liberation of chloride ion while the rate does not change in presence of the less reactive p-methoxybenzaldehyde and the product is the dinitrostilbene and not an epoxide. It was suggested that the reaction with aldehyde occurs with the intermediate anion (reactions 99 and

100) and that reaction 99 occurs faster than reaction 102 but slower than reaction 101.

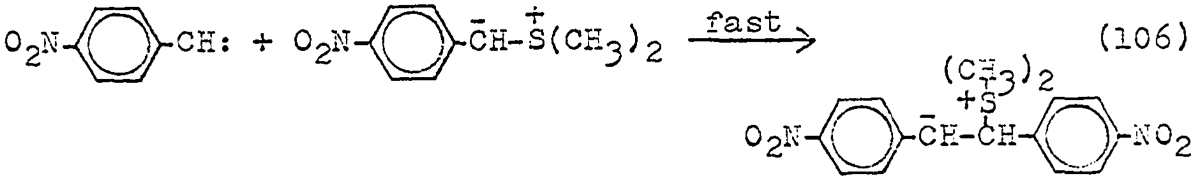
The reaction of p-nitrobenzyldimethylsulfonium tosylate with sodium hydroxide likewise results in an almost quantitative yield of p,p'-dinitrostilbene (62). The sulfur isotope effect k_{32}/k_{34} is 1.0066 ± 0.0008 and this value is discussed in terms of a reaction mechanism (62, 63). Swain and Thornton (62) argue that the value is too low for a process involving the rapid dimerization of two carbene molecules (e.g., reaction 103) for a large isotope effect is expected when an unstable intermediate like a carbene is formed because the transition state is then close to the intermediate with a weak C-S bond. The first-order solvolysis of t-butyldimethylsulfonium iodide in water has a sulfur isotope effect of 1.0177 ± 0.0014 (64), a value considerably greater than that obtained for this reaction but in agreement with the formation of a carbonium ion intermediate. For formation of either carbene or carbonium ion, the same change in carbon hybridization occurs, from sp^3 to a vacant p-orbital. However, the observed isotope effect is consistent with the following mechanism and rationalizations:



(104)



(105)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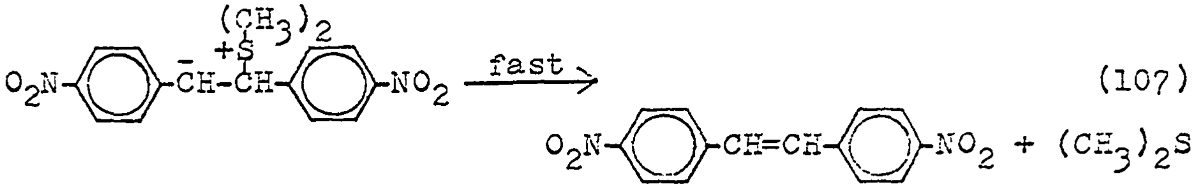
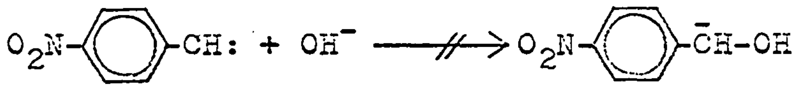

(107)

The second-order reaction of sodium hydroxide with β-phenylethyldimethylsulfonium bromide in water has a sulfur isotope effect of only 1.0015 ± 0.0009 (63). One expects a small isotope effect for decomposition of an unstable carbanion to give stable products (reaction 107) because the transition state will then be still close to the reactant, with a still strong C-S bond. If reaction 106 is reversible so that the sulfur isotope effect is determined in reactions 105 and 107, one expects it to be approximately the mean of the isotope effects for these models for reactions 105 and 107 (1.0177 and 1.0015) in agreement with the experimental value of 1.0066. If reaction 106 is irreversible or if reactions 106 and 107 are concerted, one expects the isotope effect to approximate the mean of the isotope effects for reaction 105 and 106 (1.0177 and 1.0000), since reaction 106 should have an even smaller isotope effect than reaction 107.

Rothberg and Thornton (65) undertook a further study of the reaction products of various p-nitrobenzyl 'onium salts reacting with aqueous alkali to determine what factors affect the p,p'-dinitrostilbene-forming reaction in order to see if the proposed carbene is a reasonable intermediate. In contrast to the reaction of p-nitrobenzyldimethylsulfonium tosylate with aqueous sodium hydroxide to give a quantitative yield of p,p'-dinitrostilbene, m-nitrobenzyldimethylsulfonium bromide reacts to give a 41% yield of m,m'-dinitrostilbene oxide and a 5% yield of m-nitrobenzyl alcohol; essentially the same result is obtained when the reaction is conducted in the presence of air or under a nitrogen atmosphere. p-Nitrobenzyltrimethylammonium bromide is nearly inert to refluxing aqueous sodium hydroxide, for after reacting for 72 hours 97% of the starting material can be isolated. p-Nitrobenzyltriphenylphosphonium bromide reacts to give largely triphenylphosphine oxide and p-nitrotoluene.

It is concluded by Rothberg and Thornton (65) that the combination of the resonance effect of the p-nitro group and d-orbital stabilization of the transition state for proton removal is necessary, but not sufficient, for α-elimination to form a carbene in aqueous sodium hydroxide. A delicate balance of electrical, and possibly other, effects is necessary and it may be simply of having a reactant which can form a ylid reasonably easily and which can then lose its leaving group reasonably easily to form the carbene. The experimental results are consistent with a carbene intermediate at least in the case of the *p*-nitrobenzyldimethylsulfonium ion, but the authors conclude that the quantitative yield of stilbene formed with this ion is probably an exceptional case for it is very suprising that the carbene does not undergo reactions with other nucleophiles, especially hydroxide ion which is present in rather high concentration:

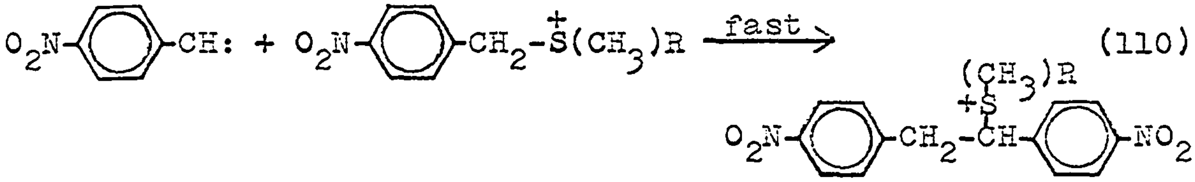

(108)


(109)

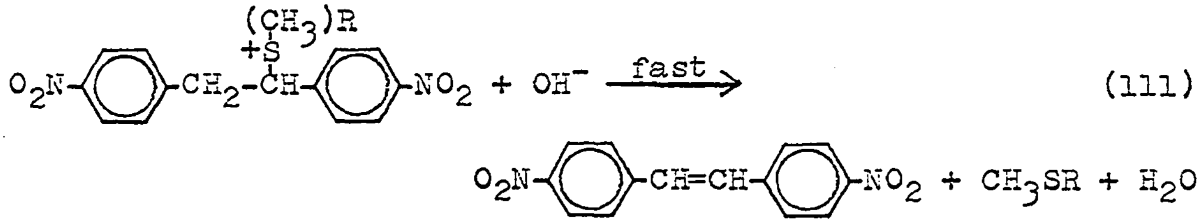
But no *p*-nitrobenzyl alcohol is detected in the reaction although it is stable under the reaction conditions.

In a following paper Rothberg and Thornton (66) synthesized and studied the following four sulfonium salts of $p\text{-}O_2NC_6H_4CH_2\overset{+}{S}(CH_3)R\overset{-}{X}$: R, X^- = C_6H_5, ClO_4^-; *p*-ClC_6H_5, ClO_4^-; *p*-$CH_3C_6H_4$, ClO_4^-; and $(CH_3)_2CH$, Br^-. Under nitrogen, the percent yields of *p*-nitrobenzyl alcohol and *p*,*p*'-dinitrostilbene were respectively: 19, 19; 10, 16; 12, 21; <0.5, 48. The first two salts both gave less alcohol and substantial amounts of *p*,*p*'-dinitrostilbene oxide when the reaction was carried out in the air. The formation of oxide is explained as resulting from attack of oxygen on *p*-nitrophenylcarbene to form *p*-nitrobenzaldehyde which then reacts with a molecule of ylid to produce *p*,*p*'-dinitrostilbene oxide.

It is noted that variation in the yield of p,p'-dinitrostilbene is relatively small when the substituents in the phenyl ring of the leaving group are varied which indicates that the electrical effect of the substituents is quite small. The quantitative yield when dimethylsulfide is the leaving group and the 48% yield of stilbene with methyl isopropyl sulfide (compared with yields of approximately 20% with methyl phenyl sulfides as leaving groups; see above) suggest that a steric factor is responsible for the differences among the various leaving groups. Thus, when dimethyl sulfide is the leaving group, the attack of p-nitrophenylcarbene on the reversibly-formed ylid anion requires the least energy and is the predominate reaction (reaction 106). Alternatively, the carbene could insert into a C-H bond of the sulfonium ion instead of reaction 106:



(110)



(111)

However, when the ylid (or the sulfonium ion) is sufficiently sterically hindered, the carbene could attack other species present, e.g., insertion reactions or attacks on the double bonds of the leaving group, reaction with oxygen to form p-nitrobenzaldehyde, and reaction with hydroxide ion or water to form p-nitrobenzyl alcohol. The fact that little or no alcohol is formed in these reactions is explained by suggesting that possibly p-nitrophenylcarbene is a very selective carbene and is simply more reactive toward ylid or other species present in solution than toward water or hydroxide. The relatively low yields of stilbene formed when groups other than dimethyl sulfide are involved in the reaction is attributed to competing Sommelet (67) and Stevens (68) rearrangements which results in large amounts of brown tar being formed.

Rothberg and Thornton (66) conclude that the proposed mechanism, in which carbene attack on an ylid or sulfonium salt is the main reaction, fits the experimental facts but is by no means proven. No experimental evidence for a carbene insertion reaction was obtained and all attempts to trap the hypothetical carbene intermediate have failed.

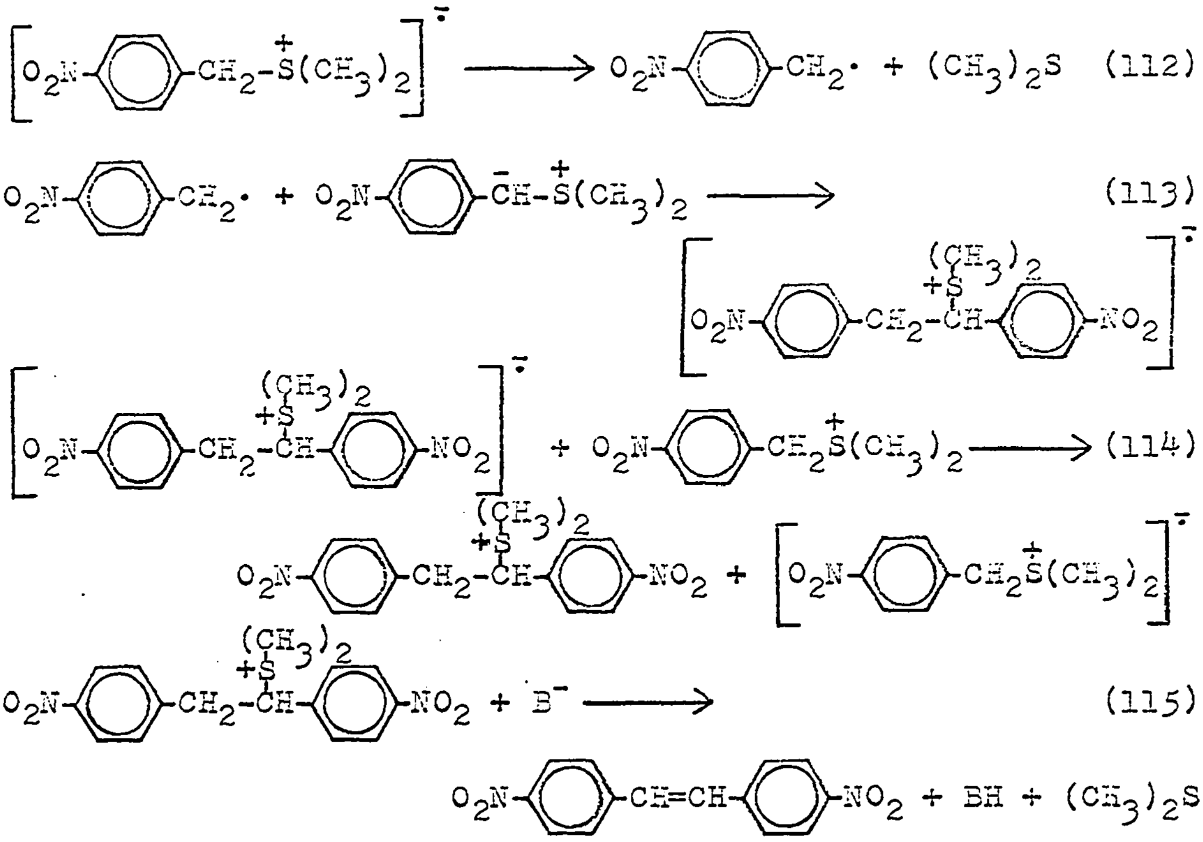
2. Results and discussion

The reaction of p-nitrobenzyldimethylsulfonium bromide with aqueous base was studied in hopes that this reaction might be found to proceed by way of a free radical chain mechanism involving a coupling of a radical with an anion:

Initiation

Same as for p-nitrobenzyl chloride (reactions 63-65)

Propagation



(112)

(113)

(114)

(115)

Here the p-nitrobenzyl radical couples with a molecule of ylid (reaction 113) instead of a true carbanion as in earlier examples. The base in reaction 115 could be either hydroxide ion or a molecule of ylid; the former is more likely on steric grounds as well as concentration considerations.

The insolubility of p,p'-dinitrostilbene makes the study of this reaction somewhat difficult since there is no method of quantitatively determining the amount of product formed when it precipitates from solution during the course of reaction. Swain and Thornton (62) followed the reaction by determining the decrease in concentration of hydroxide but this is an indirect method and one is not certain that the rate observed for disappearance of hydroxide ion necessarily equals the rate of consumption of reactant or formation of product. However, in their case, the quantitative yield of stilbene formed precludes any significant amount of hydroxide ion being consumed in side reactions.

An attempt was made to find a solvent in which the stilbene did not precipitate from the solution at least in the early stages of the reaction. Wishing to keep conditions similar to earlier work, various ethanol-water solutions were tried as reaction media. It was found that excellent yields of p,p'-dinitrostilbene were formed when the reaction was performed in refluxing water as reported (62). However, employing absolute ethanol as solvent resulted in the formation of only a small amount of very dark tar. An equal mixture of ethanol and water was found to give satisfactory yields of apparently quite pure stilbene. In all cases when p,p'-dinitrostilbene is formed, a mixture of cis and trans isomers is formed and the product melts over a large range. Refluxing this mixture in nitrobenzene with an added crystal of iodine transforms the mixture into pure trans-p,p'-dinitrostilbene, melting point 300-302°C (literature, corrected, 304-306°C--62)

An attempt to monitor the rate of the reaction by observing the increase in concentration of p,p'-dinitrostilbene or the decrease in p-nitrobenzyldimethylsulfonium salt by ultraviolet spectroscopy met with considerable difficulty and no conclusive results were obtained. The *trans*-stilbene has λ_{max} = 3540 Å (ϵ = 3.0-3.4 x 10^4); the sulfonium salt has λ_{max} = 2610 Å (ϵ = 2.3-2.6 x 10^4). Conducting an experiment in 50:50 ethanol:water at 30°C in the dark with a 0.02 M concentration of the sulfonium salt and 0.03 M sodium hydroxide and removing aliquots which are simultaneously quenched and diluted produces an ultraviolet spectrum which indicates approximately 30% of the theoretical amount of stilbene is formed after 7 hours. The optical density of the sulfonium salt has decreased about 38% in this same time and the maximum has shifted slightly to 2640 Å. Allowing the reaction to continue an additional 15 hours produces 40% of the stilbene and a shorter wavelength maximum now at 2750 Å. Conducting a similar experiment except this time with irradiation at 13.5°C results in a decreased maximum shifted to 2730 Å after 3 hours reaction time but with apparently only a small amount of stilbene formed (10%). However, a yellow precipitate appears in the reaction solution after approximately 8 minutes reaction time. This precipitate is stilbene as shown by infrared spectroscopy.

The appearance of a new shorter wavelength absorption at approximately 2750 Å indicates that another product besides *p*,*p*'-dinitrostilbene is being formed in the reaction. The following conceivable products all have absorption maximum in this general region: *cis*-*p*,*p*'-dinitrostilbene oxide (2710 Å), trans-p,p'-dinitrostilbene oxide (2830 Å), p-nitrotoluene (2725 Å), p,p'-dinitrobibenzyl (2755 Å), and p-nitrobenzyl alcohol (2720 Å). Thin layer chromatography indicated that p,p'-dinitrostilbene was the predominate product in the above two reactions but that other products were formed although probably in low yield. Although not definitely proven, these minor products appeared by thin layer chromatography to be the stilbene oxides and possibly a small amount of p-nitrobenzyl alcohol. However, these conclusions are highly tentative since the bibenzyl and the stilbene oxides have nearly identical R_f values and p-nitrobenzyl alcohol has a very small R_f value.

It is not certain if the formation of these minor products is a result of changing the solvent from water to 50:50 ethanol:water. An experiment was conducted in which a previously degassed aqueous solution of p-nitrobenzyldimethylsulfonium bromide was reacted with degassed aqueous sodium hydroxide solution at room temperature for 2½ hours. The reaction was quenched with acetic acid and the small amount of yellow solid was collected by filtration, washed, and dried. An ethanol solution of this solid exhibited an absorption at 3540 Å due to p,p'-dinitrostilbene, but even stronger absorption appeared at 2770 Å. This result may indicate that the reaction of the sulfonium salt with aqueous base, at least at lower temperatures, does not result in a quantitative yield of p,p'-dinitrostilbene (62, 65). In any case, these results eliminate the possibility of following the course of the reaction by monitoring the absorbance of the sulfonium salt at 2610 Å.

In addition to the limited solubility of p,p'-dinitrostilbene, another factor was discovered which precluded monitoring its formation by ultraviolet spectroscopy at 3540 Å. When an ethanol solution of trans-p,p'-dinitrostilbene is allowed to stand in the presence of light, the absorbance at 3540 Å diminishes and new lower wavelength band appears. If a basic ethanolic solution of the trans-stilbene is irradiated with a sunlamp the 3540 Å peak almost disappears and a new maximum at 2670 Å appears along with several other minor peaks in the ultraviolet spectrum. It is not likely that this new maximum is due to cis-p,p'-dinitrostilbene (69) but perhaps results from some reduction product of the dinitro compound (8).

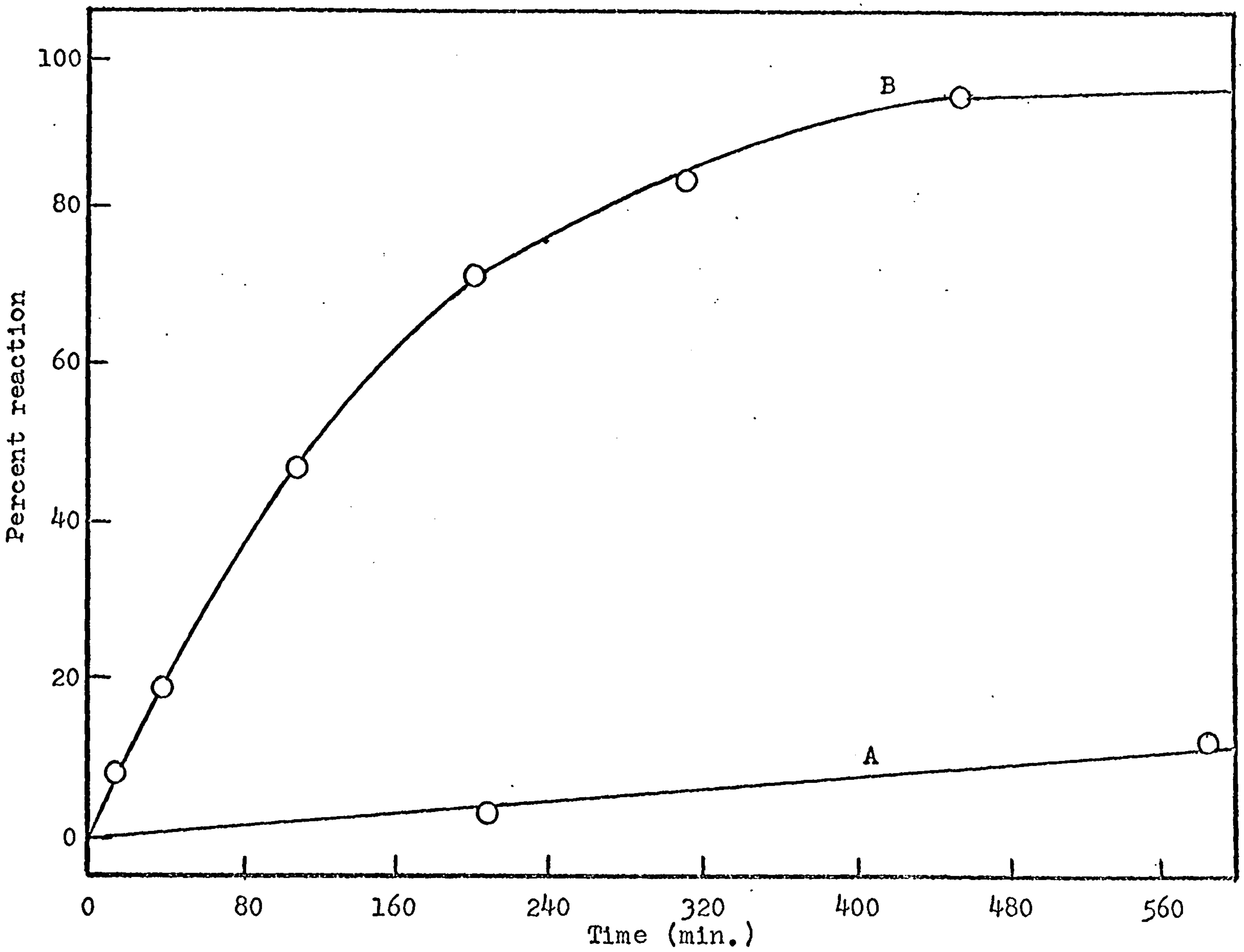
Hexaphenylethane and the sodium salt of 2,4-dinitrobenzenesulfonic acid were added to the reaction of p-nitrobenzylsulfonium bromide and sodium hydroxide in an attempt to inhibit the formation of p,p'-dinitrostilbene. Due to the difficulties considered above, however, inconclusive results were obtained. It was decided to study the reaction by following the rate of disappearance of sodium hydroxide by potentiometic titration.

Figure 22 shows the effect of irradiation versus dark for the reaction of 0.020 M sulfonium compound and 0.030 M sodium

Figure 22. Reaction of 0.020 M p-nitrobenzyldimethylsulfonium bromide with 0.030 M sodium hydroxide under nitrogen in 50:50 ethanol:water at 12.5°C

A. Dark

B. Illuminated


Percent reaction
0
20
40
60
80
100
Time (min.)
0
80
160
240
320
400
480
560
A
B

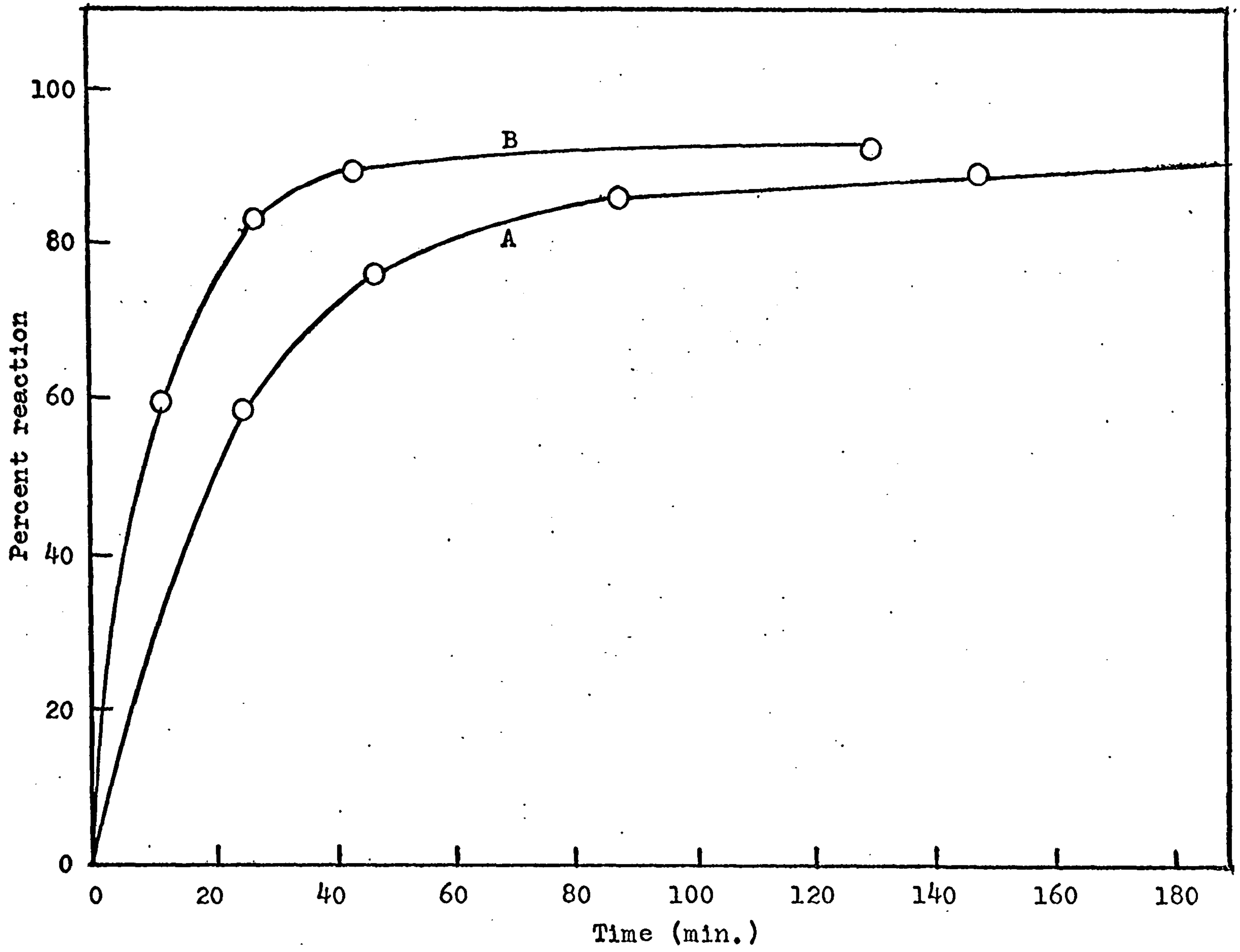
hydroxide in 50:50 ethanol:water at 12.5°C. It is assumed that one molecule of p,p'-dinitrostilbene is formed for every two molecules of hydroxide ion consumed. Note that there is only a very slow reaction in the dark, 38% yield of stilbene formed after 22 hours. With irradiation the reaction is virtually complete after 8 hours. Figure 23 shows the effect of light on the rate of the reaction when the solvent is 90:10 ethanol:water and the temperature is 30°C. There is a rapid reaction even in the dark in this case, but it is seen that the rate of the reaction is still greater for the photolyzed than for the dark reaction. In pure water the reaction is much slower at 13°C than either case but is still catalyzed by light; after 20 hours reaction time only 12.5% of stilbene is formed in the dark while 31.4% is formed in 22 hours when the reaction solution is irradiated. This pronounced increase in rate of reaction as the percentage of ethanol in the solvent is increased is probably an effect of the enhanced basicity of the ethanolic solutions over that of pure water. The more basic the solution, the higher the concentration of ylid (reaction 104). This conclusion is substantiated by a dramatic visual observation: the initial reaction solution when pure water is the solvent is practically colorless while that of 90:10 ethanol:water is blood red due to a high concentration of ylid (62).

Employing the usual technique of determining the effect of oxygen on the reaction resulted in oxygen absorption and

Figure 23. Reaction of 0.020 M p-nitrobenzyldimethylsulfonium bromide with 0.030 M sodium hydroxide under nitrogen in 90:10 ethanol:water at 30°C

A. Dark

B. Illuminated


100
80
60
40
20
0
Percent reaction
B
A
0
20
40
60
80
100
120
140
160
180
Time (min.)

inhibition of p,p'-dinitrostilbene formation (Figure 24). It is seen that approximately 0.25 mole of oxygen is absorbed for every mole of sulfonium salt in the reaction. A 68% yield of p,p'-dinitrostilbene oxide (melting point, 202.5-204.5°C; literature, 200-201°C--60) was isolated along with 23% crude p-nitrobenzoic acid. The formation of the stilbene oxide was not unexpected (66) and does not distinguish between the carbene mechanism (reactions 104-107) and the postulated free radical chain mechanism (reactions 112-115). It is not possible to ascertain if molecular oxygen attacked the p-nitrobenzyl radical, or the p-nitrophenyl carbene, or the ylid itself. Presumably it attacks one of the latter (66, 70) for if a chain mechanism were operative to produce the radical only enough oxygen should react to inhibit the chain process and the rate of oxygen uptake would be quite slow.

Figure 25 illustrates the effect of an added 10% of cupric chloride to the reaction solution; it is seen that there is only a small effect. However, when the sodium hydroxide solution was added at the start of the reaction, a suspension appeared which conceivably was cupric hydroxide. In view of this, the experiment may be meaningless for the inhibitor might not have been present in the reaction solution.

Hexaphenylethane exerts some influence on the reaction as is obvious from Figure 26 where the rate of reaction at 13 C° in 90:10 ethanol:water is plotted. It appears that the reaction may be inhibited somewhat at the onset but after

Figure 24. Reaction of 0.10 M (5.00 mmoles) p-nitrobenzyldimethylsulfonium bromide and 0.20 M (10.0 mmoles) sodium hydroxide with oxygen in 50:50 ethanol:water and room light at ca. 30°C

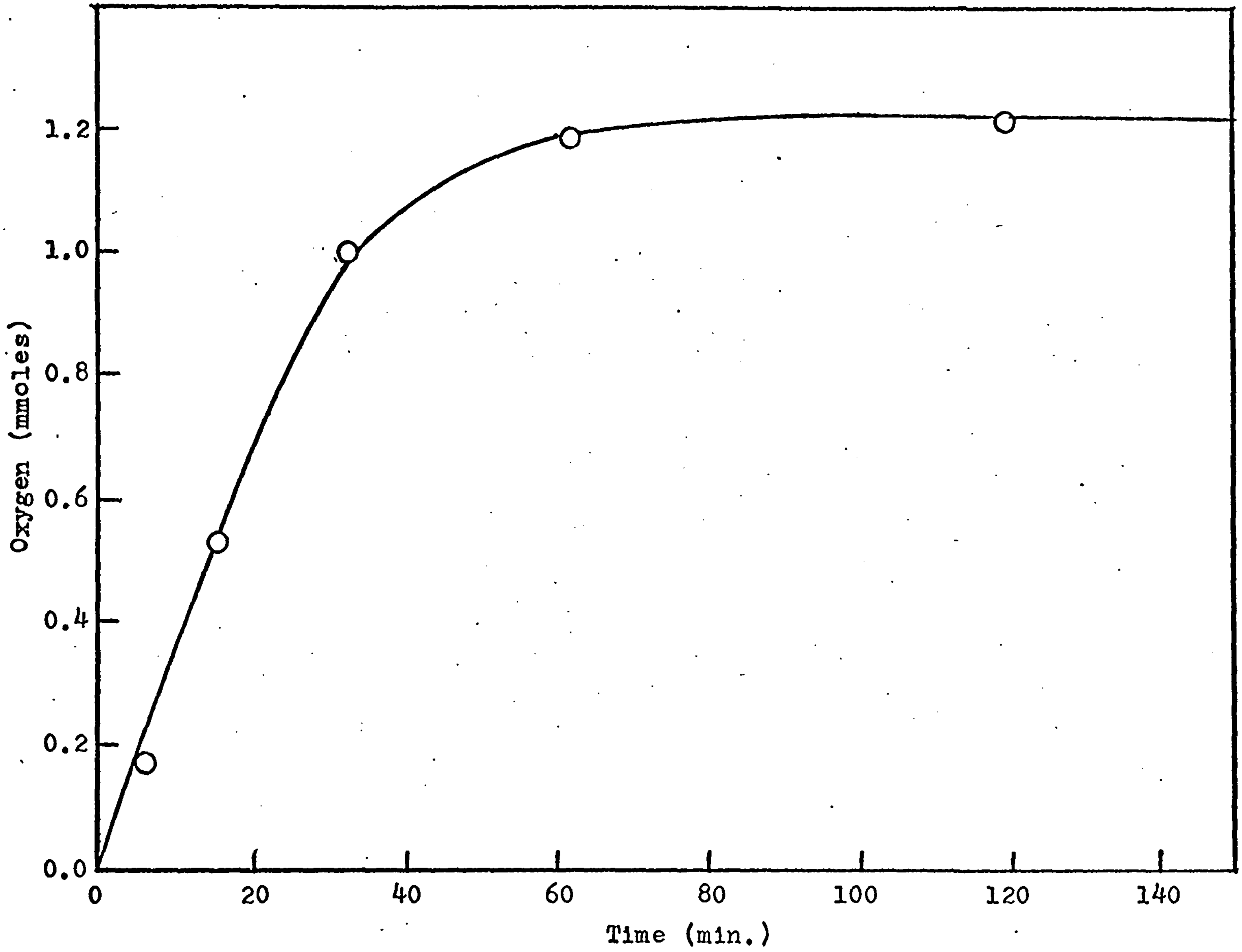
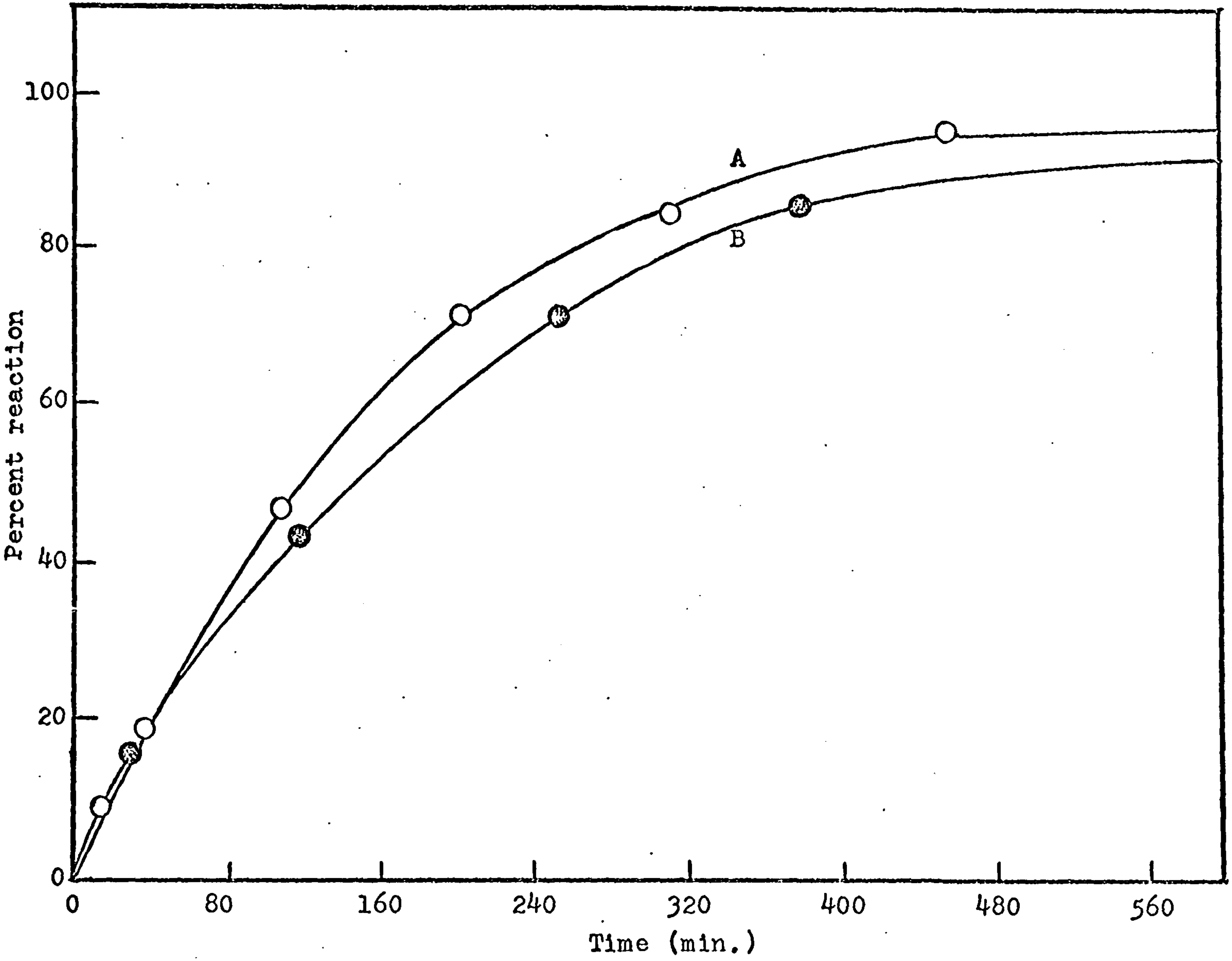

Oxygen (mmoles)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Time (min.)
0
20
40
60
80
100
120
140

Figure 25. Reaction of 0.020 M p-nitrobenzyldimethylsulfonium bromide with 0.030 M sodium hydroxide under nitrogen in 50:50 ethanol:water at 12.5°C

A. Illuminated

B. Illuminated in presence of 0.002 M cupric chloride

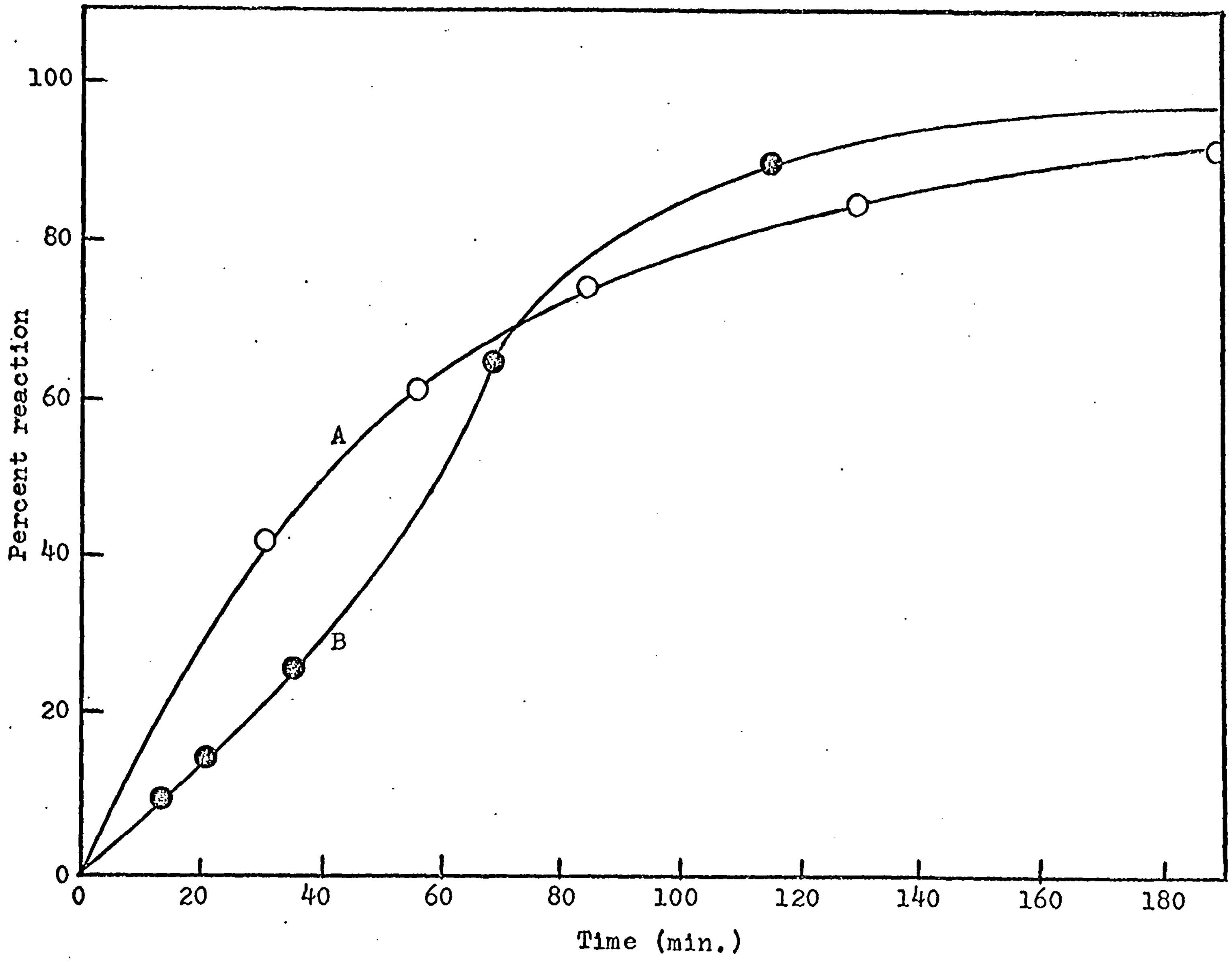


Percent reaction
0
20
40
60
80
100
Time (min.)
0
80
160
240
320
400
480
560
A
B

Figure 26. Reaction of 0.020 M p-nitrobenzyldimethylsulfonium bromide with 0.030 M sodium hydroxide under nitrogen in 90:10 ethanol:water at 13°C

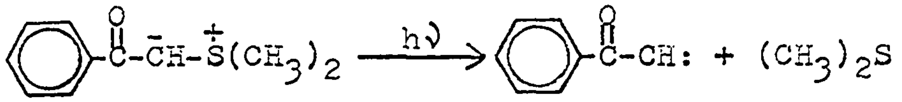
A. Illuminated

B. Illuminated in presence of 0.0016 M hexaphenylethane


Percent reaction
0
20
40
60
80
100
Time (min.)
0
20
40
60
80
100
120
140
160
180
A
B

approximately 40 minutes proceeds unrestrained. The initial rate of reaction is about one-half that exhibited by the reaction without the triphenylmethyl inhibitor. The fact that the reaction is not inhibited completely at the start may be indicative of side reactions occurring under these conditions. A large scale reaction of p-nitrobenzyldimethylsulfonium bromide with sodium hydroxide in 90:10 ethanol:water was conducted to determine the effect of this amount of alcohol on the course of the reaction. At 14°C in room light a 60.5% yield of p,p'-dinitrostilbene was isolated by simply filtering the reaction solution after it had reacted for 9 hours. Upon standing, the filtrate produced a small amount of gluey, yellow substance. Removal of the ethanol from the filtrate produced a dark oil at the bottom of the water layer. No attempt was made to identify these substances which obviously were mixtures. This experiment demonstrates that the reaction in 90:10 ethanol:water does not give a quantitative yield of stilbene but that this compound is still the predominant product.

The effect of free radical inhibitors on the reaction of the p-nitrobenzylsulfonium salt with base is not decisive in that a free radical chain process is neither demanded by the results nor is it absolutely excluded. Just as with the diphenyliodonium system discussed in the previous section, the catalytic effect of light is explicable in terms of at least two possible mechanisms and does not necessarily indicate that a free radical chain process is operative. In the case at hand, the carbene mechanism postulated by Swain and Thornton (62) is compatible with the light catalysis for it has been shown by Trost (71) that dimethylsulfoniumphenacylid is decomposed by light to form the carbene: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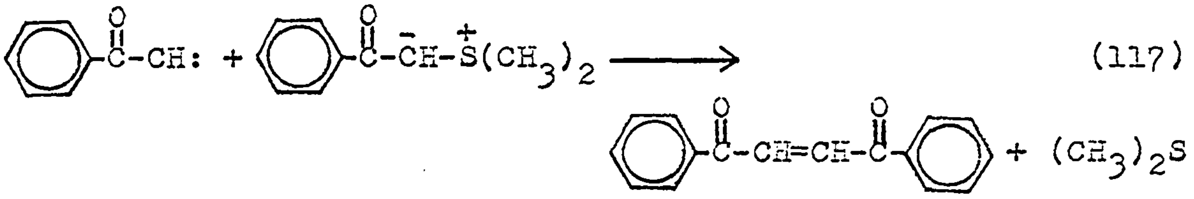
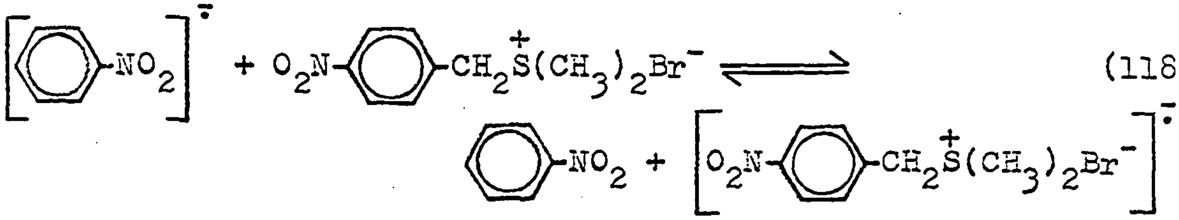

(117)

The reaction of the carbene with the ylid to produce the stilbene is perfectly analogous to the reaction of *p*-nitrophenyl carbene with *p*-nitrobenzldimethylsulfonium ylid to produce *p*,*p*'-dinitrostilbene (reactions 106 and 107). However, the photolytic decomposition of the phenacyl ylid clearly involves benzoylcarbene as an intermediate for if the reaction is conducted in the presence of cyclohexene benzoylnorcarane is produced. If the above ylid is irradiated in ethanol or isopropanol large amounts of acetophenone are isolated as well as other products; the same products in very similar ratios are produced in the decomposition of diazoacetophenone (72) which indicates that benzoylcarbene is definitely an intermediate in the decomposition of ylid. Interestingly, this observation explains the increasing amounts of side products in the reaction of *p*-nitrobenzyldimethylsulfonium bromide with base as the ratio of ethanol to water is increased. Trost has also shown that the benzoylcarbene reacts approximately 8000 times faster with the ylid (reaction 117) than it does with cyclohexene. This may explain why Rothberg and Thornton (66) were unsuccessful in their attempts to trap the proposed carbene intermediate in their postulated mechanism.

An experiment was conducted in which a large excess of nitrobenzene was present in the reaction solution. It was hoped that the nitrobenzene radical anion formed when the solution was irradiated (10) might transfer an electron to the *p*-nitrobenzylsulfonium salt to produce the corresponding radical anion which would eliminate dimethylsulfide and form the *p*-nitrobenzyl radical. The overall result of such a process would be to catalyze the formation of *p*,*p*'-dinitrostilbene. Figure 27 illustrates that the added nitrobenzene has a negligible effect on the rate of reaction. A possible explanation for the absence of any catalysis is that the nitrobenzene radical anion does not undergo an electron transfer with *p*-nitrobenzyldimethylsulfonium bromide:

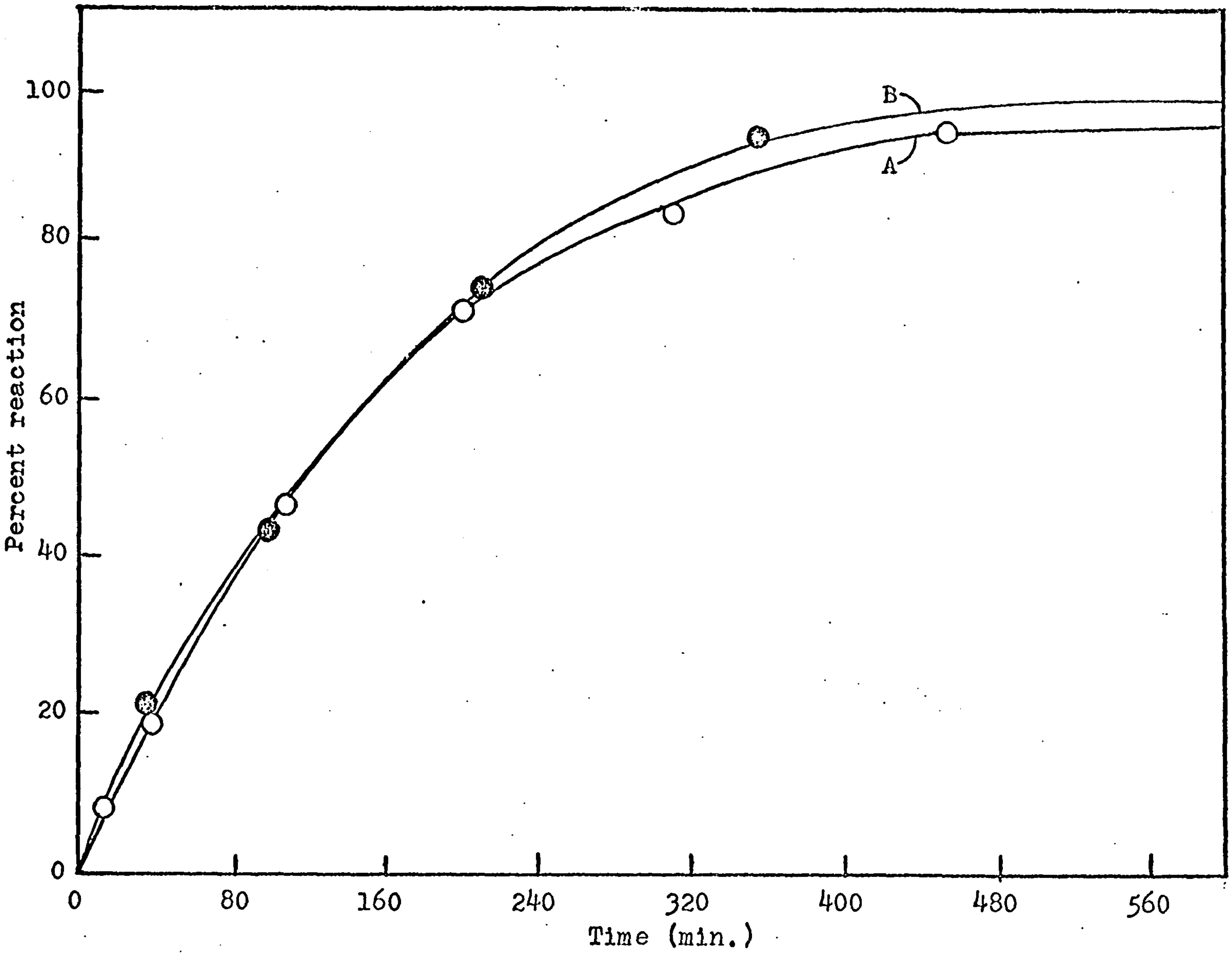


(118)

Figure 27. Reaction of 0.020 M *p*-nitrobenzyldimethylsulfonium bromide with 0.030 M sodium hydroxide under nitrogen in 50:50 ethanol:water at 12.5°C

A. Illuminated

B. Illuminated in presence of 1.0 M nitrobenzene


100
80
60
40
20
0
Percent reaction
0
80
160
240
320
400
480
560
Time (min.)
B
A

Alternatively, perhaps the reverse reaction 118 is a facile process and the added nitrobenzene might actually inhibit the overall reaction just as p-dinitrobenzene was shown to be an effective inhibitor for systems discussed earlier. A fortuitous combination of catalysis and inhibition could result in the same rate as that exhibited for the reaction without added nitrobenzene.

In spite of the compatability of the carbene mechanism with the light catalysis, the effect of light might still be explained as initiating a free radical chain mechanism as was proven for earlier systems studied in this work. A quantum yield experiment was conducted to determine if the light might not indeed be initiating a chain process. If this is the case a quantum yield of greater than unity should be obtained. A reaction employing the usual concentrations of reactants (0.02 M p-nitrobenzyldimethylsulfonium bromide and 0.03 M sodium hydroxide) in 25:75 ethanol:water as solvent was conducted in a Rayonet (Srinivasan-Griffin) Photochemical Reactor using 4 low pressure mercury lamps (2537 Å) and a quartz Hanovia photochemical immersion vessel to contain the reactants. The inner chamber of the quartz reaction vessel is approximately 4 cm. in diameter and 25 cm. in length. p-Nitrobenzyldimethylsulfonium bromide exhibits an absorption maximum at 2610 Å with an extinction coefficient of 2.5×10^4; trans-p,p'-dinitrostilbene has a minimum of absorption in this region. With a 0.02 M concentration of p-nitrobenzyldimethylsulfonium salt, the incident light need travel only 0.004 cm. before it is 99% absorbed by the sulfonium salt thus assuring that virtually the total emitted light is absorbed by the reactant under the reaction conditions. The temperature was 14° ± 0.5°C and the reaction was photolyzed for 96.3 minutes during which time the reaction proceeded to 9.3% completion. The Rayonet Reactor emits 1.65×10^{16} photons/cm.^{3}-sec. using 16 lamps; for 200 ml. of reaction solution after 96.3 minutes irradiation this corresponds to approximately 5×10^{21} photons for 4 lamps and gives a very approximate quantum yield of 0.02:

$$\Phi = \frac{1.1 \times 10^{20} \text{ molecules } \underline{p},\underline{p}'\text{-dinitrostilbene formed}}{5.0 \times 10^{21} \text{ photons emitted}} = 0.02$$

Such a low quantum yield obviously does not lend support to the postulation of a chain mechanism; however, the low value can be rationalized. First of all, irradiation at 2537 Å causes a $\pi \rightarrow \pi^*$ excitation of the p-nitrobenzylsulfonium salt and it is known that the $n \rightarrow \pi^*$ excited state is involved in hydrogen abstraction (8, 9). If, indeed, the chain mechanism is initiated by a light induced hydrogen abstraction by the excited nitro group (reactions 63-65), perhaps there is an inefficient crossover from the $\pi \rightarrow \pi^*$ to the $n \rightarrow \pi^*$ excited states. Such an occurrence would result in light absorption but no chain initiation and consequently a low quantum yield would result. Secondly, it has been shown (8) that hydrogen abstraction by the n$\rightarrow\pi^*$ excited nitrobenzene is not a very efficient process due to a combination of inefficient intersystem crossing (from the initially formed n$\rightarrow\pi^*$ singlet to the chemically active triplet) and a large deactivation rate constant for the triplet. The quantum yield of disappearance of nitrobenzene in isopropyl alcohol is only about 0.01 which indicates that for every 100 photons of light absorbed only one act of hydrogen abstraction takes place. If it can be assumed that such a value also applies to p-nitrobenzyldimethylsulfonium bromide, this fact alone could account for the low quantum yield experimentally obtained for the reaction of this compound. Finally, because of its low solubility, p,p'-dinitrostilbene precipitates for the reaction solution almost from the start of the reaction. This suspension of stilbene undoubtedly reflects some (much?) of the incident light which then is not available to activate any of the reacting nitrosulfonium salt; such an effect would contribute to a lowering of the quantum yield.

In spite of the above argument, however, most of the experimental evidence suggests that a free radical chain mechanism is not operative in this system. The postulated carbene mechanism (62, 65, 66) is not excluded by any of the results and may, indeed, be the process by which p,p'-dinitrostilbene is formed. However, another mechanistic possibility must be considered, but a discussion of this will be deferred until later.

It was of interest to investigate the reaction of the lithium salt of 2-nitropropane with p-nitrobenzyldimethylsulfonium bromide. As discussed earlier in this thesis, the reaction of this anion with p-nitrobenzyl chloride was shown to be a free radical chain process involving the reaction of the p-nitrobenzyl free radical with the anion as an important propagation step. Changing the leaving group from chloride ion to dimethyl sulfide would be the only alteration in the reacting species and it was anticipitated that such a change should not affect the course of the reaction too drastically.

It was shown that the carbon alkylated product is produced in quite good yield in the reaction of the lithium salt of 2-nitropropane with the p-nitrobenzyl sulfonium salt in ethanol solutions. Moreover, just as with p-nitrobenzyl chloride, the reaction can be both catalyzed and inhibited. Figure 28 shows that light enhances the rate of reaction significantly although there is a quite rapid reaction even in the dark. Figure 29 illustrates that a 10% concentration of p-dinitrobenzene has only a slight effect on both the light and dark reactions. This result is to be contrasted with the effect of small amounts of p-dinitrobenzene on the rate of reaction of this anion with 2-halo-2-nitropropane and with p-nitrobenzyl chloride in both ethanol and DMF as discussed earlier. Hexaphenylethane, however, is an effective inhibitor

Figure 28. Formation of coupled product in the reaction of 0.150 M lithium salt of 2-nitropropane with 0.075 M p-nitrobenzyldimethylsulfonium bromide under nitrogen in ethanol at 30° C

A. Dark

B. Illuminated

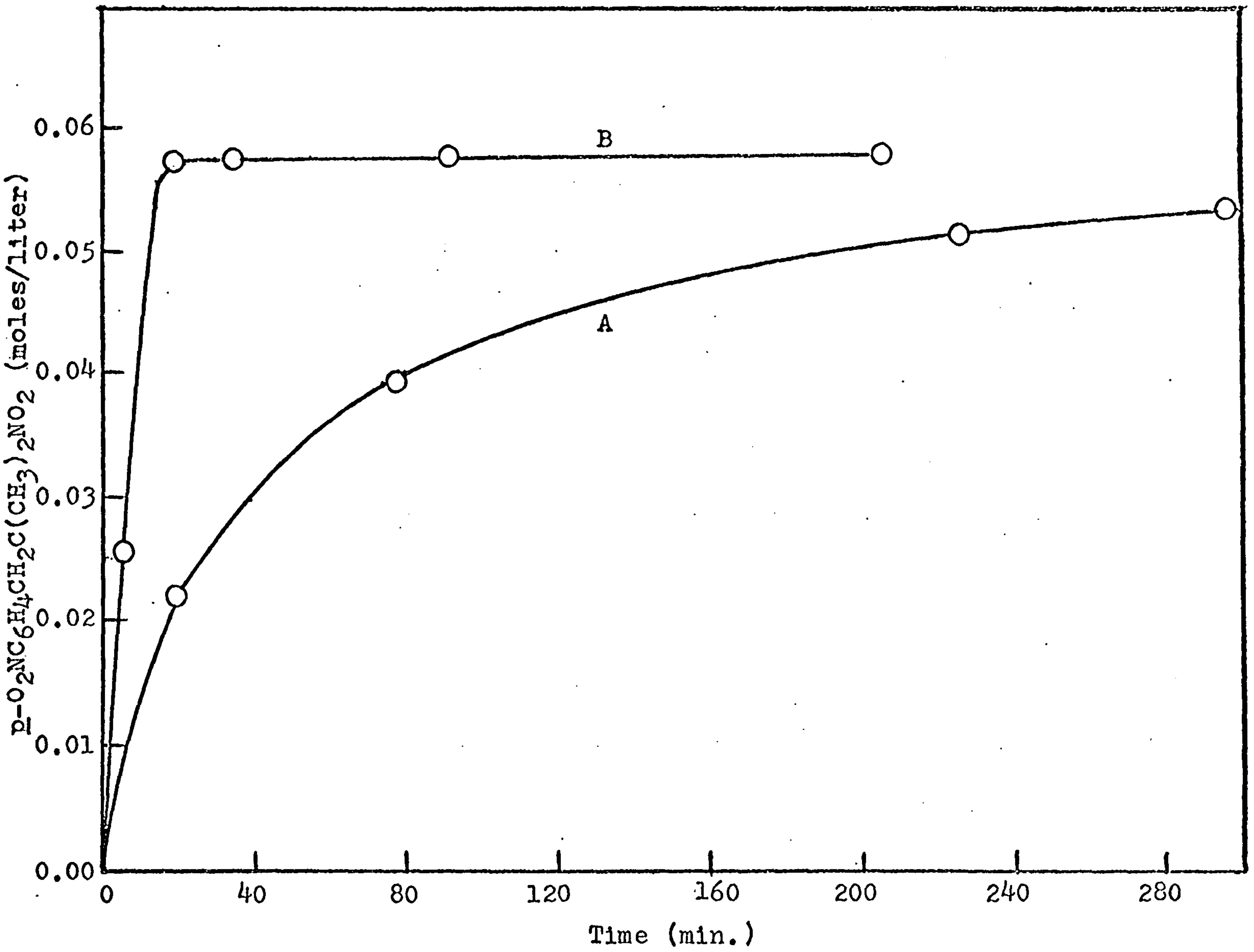
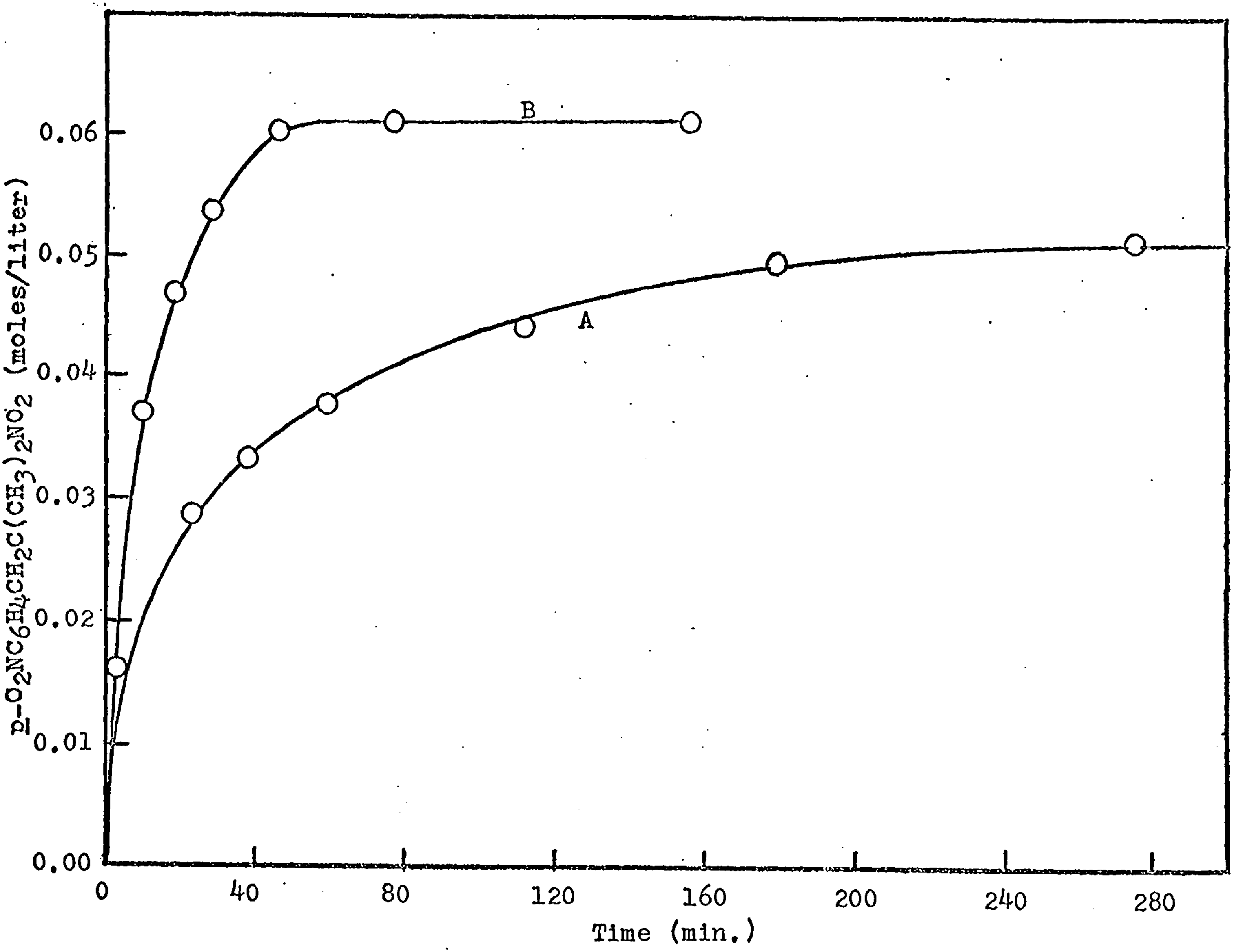

$p\text{-}O_2NC_6H_4CH_2C(CH_3)_2NO_2$ (moles/liter)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
B
A
0
40
80
120
160
200
240
280
Time (min.)

Figure 29. Formation of coupled product in the reaction of 0.150 M lithium salt of 2-nitropropane with 0.075 M p-nitrobenzyldimethylsulfonium bromide in the presence of 0.0075 M p-dinitrobenzene under nitrogen in ethanol at 30° C

A. Dark

B. Illuminated


B
A
0.06
0.05
0.04
0.03
0.02
0.01
0.00
p-O2NC6H4CH2C(CH3)2NO2 (moles/liter)
0
40
80
120
160
200
240
280
Time (min.)

for the reaction; Figure 30 illustrates the effect of various amounts of added hexaphenylethane. It is seen that this inhibitor completely quenches the reaction for a period of time which depends on its concentration. Also noteworthy is the fact that the yield of coupled product is also dependent upon the amount of inhibitor present in the reaction. The longer the reaction is suppressed, the lower is the final yield of carbon alkylated product. Such a result illustrates that another process is occurring which consumes reactants and is not effected by the free radical inhibitor. Although not proven, it is probable that this side reaction results in formation of p,p'-dinitrostilbene, possibly via a carbene mechanism.

When the reaction of the lithium salt of 2-nitropropane with the p-nitrobenzylsulfonium salt is conducted in the presence of oxygen a somewhat suprising result is observed. As anticipated, no carbon alkylated coupled product is formed but the 2-nitro-2-propyl anion apparently is not oxidized either. Instead, a 64% yield of p,p'-dinitrostilbene oxide is isolated. Figure 31 shows that the amount of oxygen reacted corresponds to oxidation of the p-nitrobenzylsulfonium compound only and that the 2-nitro-2-propyl anion is not oxidized (compare with Figures 1, 4, 12, and 24). The anion must be sufficiently basic to react with the sulfonium compound and form the ylid which then either reacts directly with oxygen or undergoes an α-elimination to produce the carbene which is

Figure 30. Formation of coupled product in the reaction of 0.150 M lithium salt of 2-nitropropane with 0.075 M p-nitrobenzyldimethylsulfonium bromide under nitrogen in ethanol at 30°C

A. Illuminated

B. Illuminated in presence of 0.0037 M hexaphenylethane

C. Illuminated in presence of 0.0075 M hexaphenylethane

D. In dark in presence of 0.0075 M hexaphenylethane

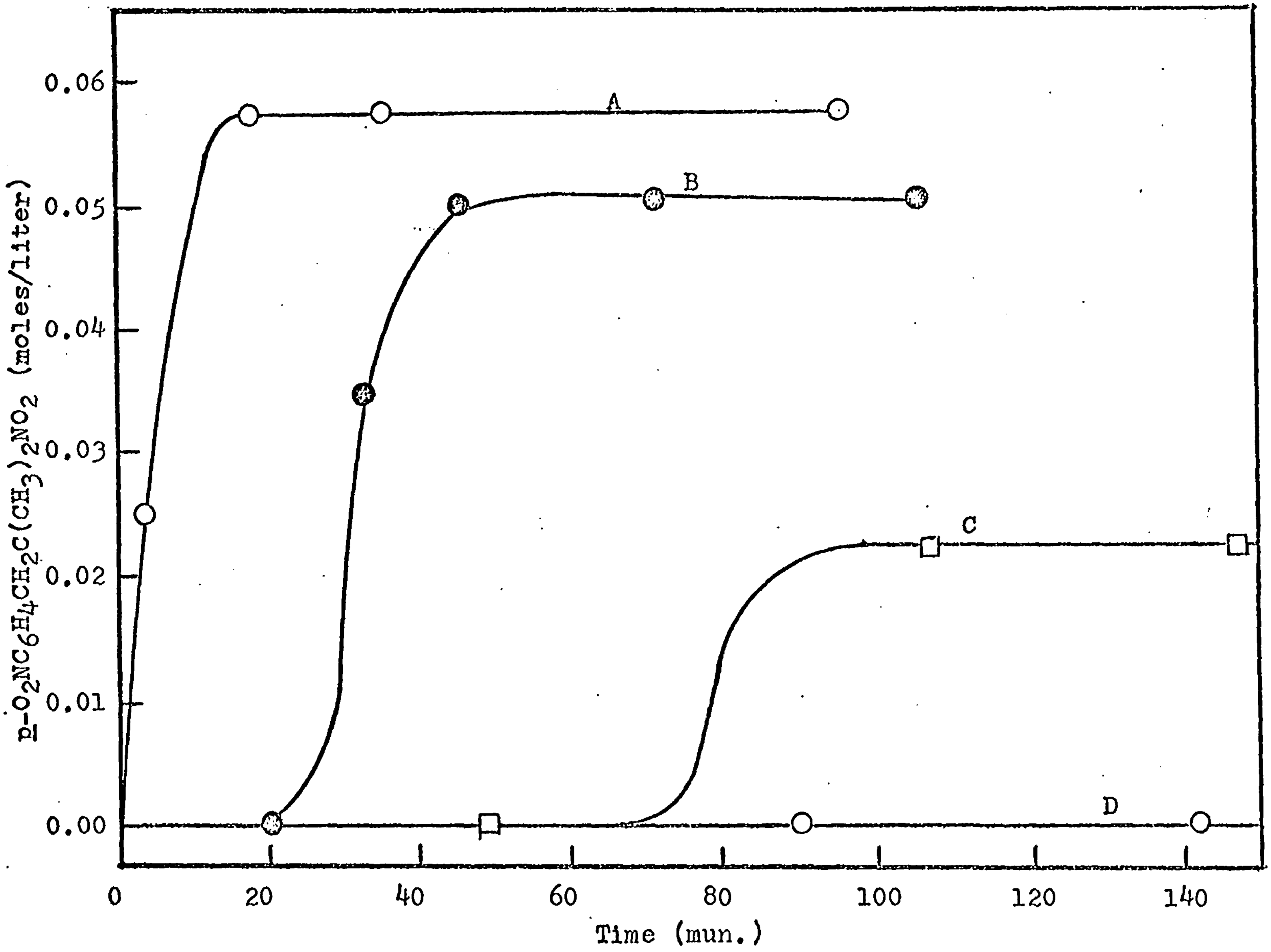
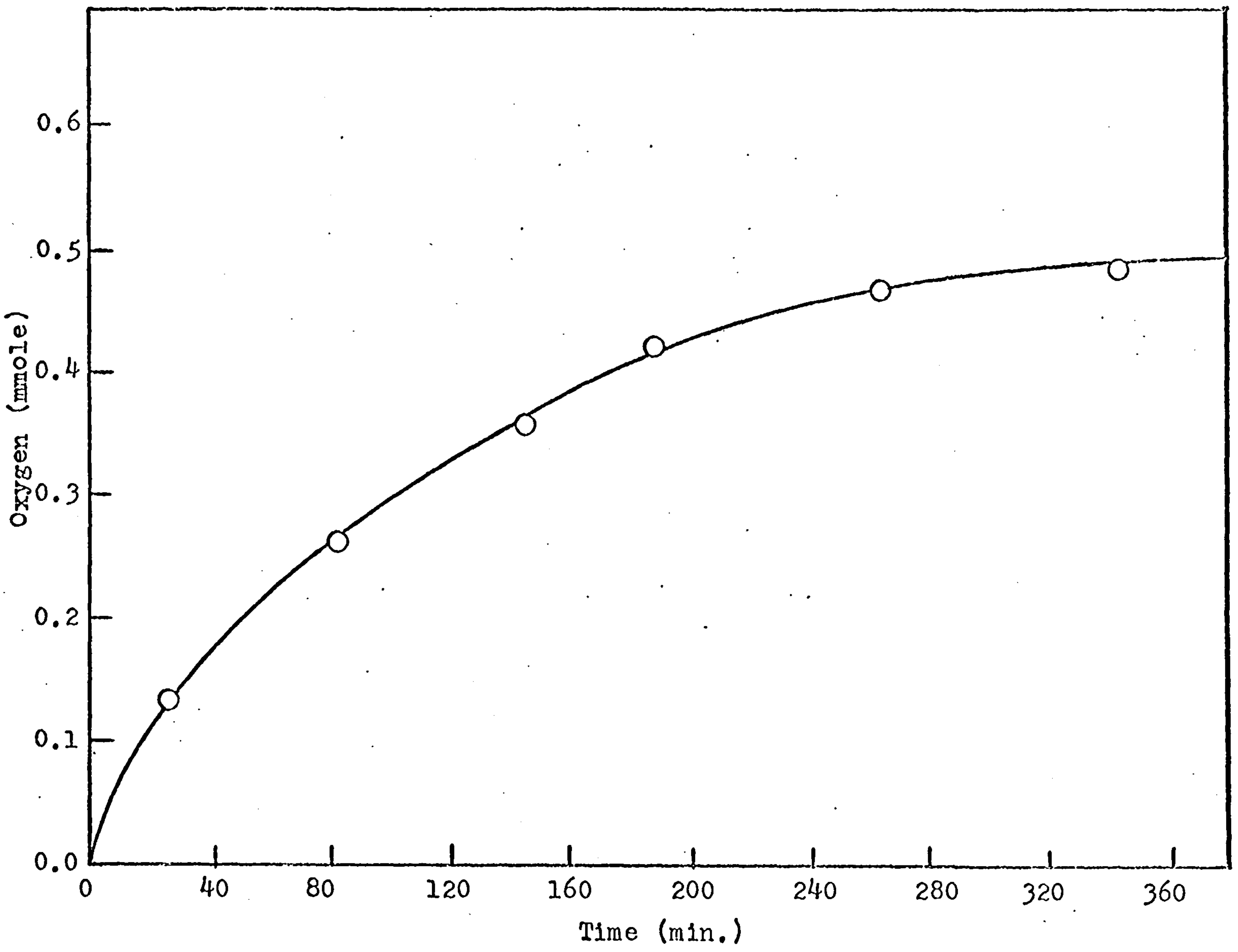

A
B
C
D
0.06
0.05
0.04
0.03
0.02
0.01
0.00
p-$O_2NC_6H_4CH_2C(CH_3)_2NO_2$ (moles/liter)
0
20
40
60
80
100
120
140
Time (mun.)

Figure 31. Reaction of 0.150 M (5.00 mmoles) lithium salt of 2-nitropropane and 0.075 M (2.50 mmoles) *p*-nitrobenzyldimethylsulfonium bromide with oxygen in ethanol and room light at ca. 30°C (0.655 mmoles oxygen absorbed after 1312 minutes).


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Oxygen (mmole)
0
40
80
120
160
200
240
280
320
360
Time (min.)

then oxidized to p-nitrobenzaldehyde. Reaction of this aldehyde with ylid then produces p,p'-dinitrostilbene oxide.

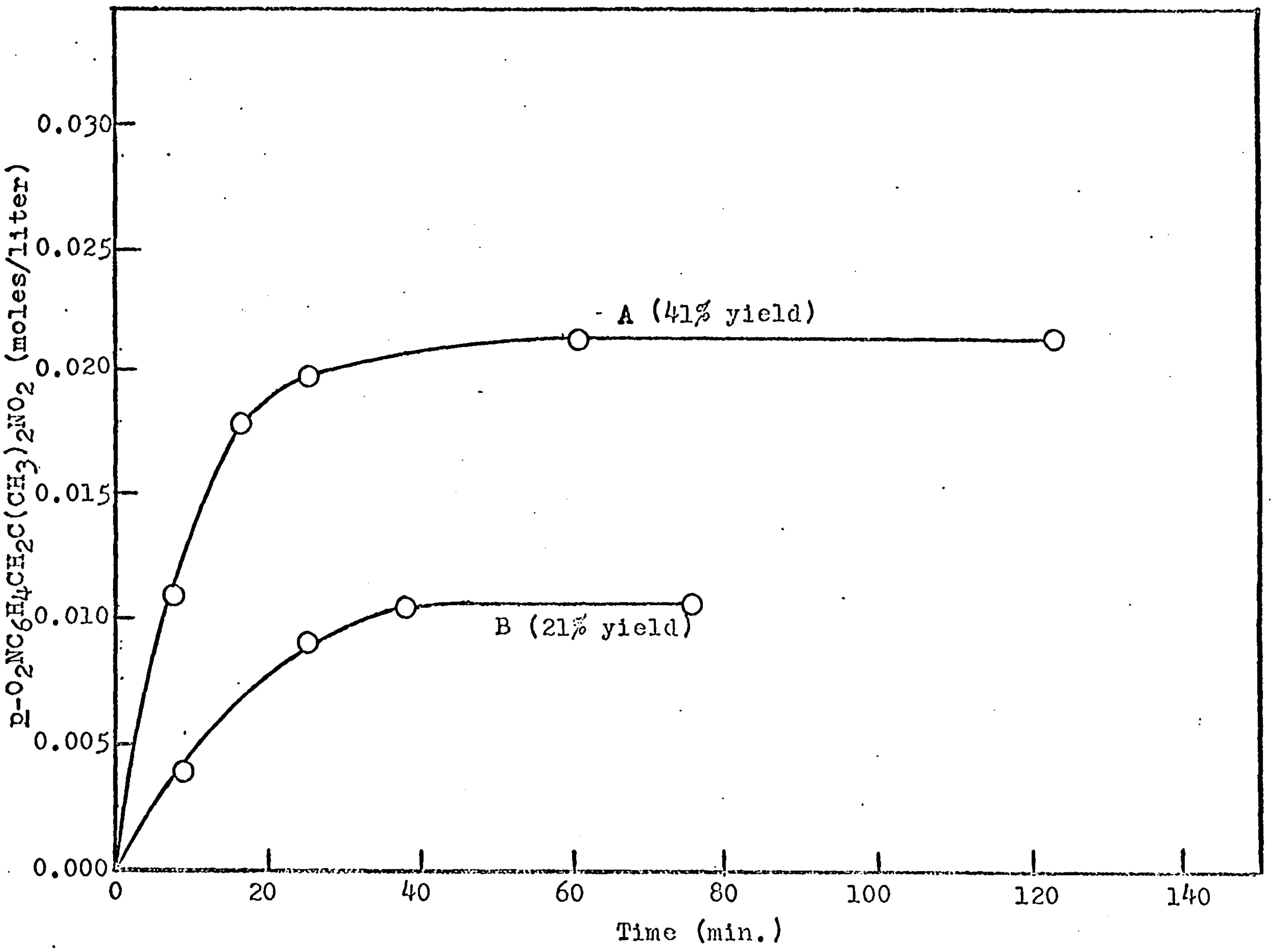
An experiment was conducted in which the lithium salt of 2-nitropropane was added to a reaction of the sulfonium salt with sodium hydroxide in 90:10 ethanol:water. Under these conditions a relatively high concentration of ylid is present in solution and there is a quite rapid reaction (Figure 23). Figure 32 illustrates that a yield of carbon alkylated coupled product of 41% is obtained under these conditions. The addition of a small amount of p-dinitrobenzene to the reaction results in a lower yield of coupled product. These results are understandable in terms of a free radical chain mechanism resulting in the formation of the coupled product while the stilbene is produced via some alternate process. The inhibitory effect of p-dinitrobenzene in this case may be a result of changing the solvent. Alternatively, the proposed carbene intermediate may react with the 2-nitro-2-propane anion to produce the coupled product in competition with formation of the stilbene by a similar process in which the carbene attacks the ylid anion.

A related 'onium salt was also briefly investigated. Shechter and Kaplan (73) have reported that the sodium salt of 2-nitropropane reacts with p-nitrobenzyltrimethylammonium iodide in refluxing ethanol to yield 63% of the coupled product, 2-methyl-2-nitro-p-nitrophenylpropane, after 30 hours. It was found, however, that no carbon-alkylated product is

Figure 32. Formation of coupled product in the reaction of 0.100 M lithium salt of 2-nitropropane with 0.050 M *p*-nitrobenzyldimethylsulfonium bromide and 0.075 M sodium hydroxide under nitrogen in 90:10 ethanol:water at 30°C

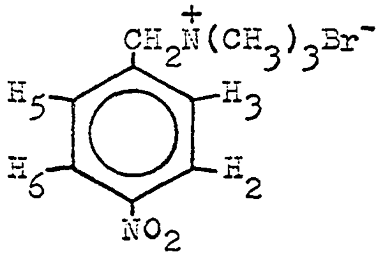
A. Dark

B. In dark and in presence of 0.005 M *p*-dinitrobenzene



0.030
0.025
0.020
0.015
0.010
0.005
0.000
$\underline{p}$-$O_2NC_6H_4CH_2C(CH_3)_2NO_2$ (moles/liter)
A (41% yield)
B (21% yield)
0
20
40
60
80
100
120
140
Time (min.)

formed in this reaction at 30°C even when the reaction solution is irradiated for 7 hours. Such conditions result in nearly complete conversion for p-nitrobenzyl chloride and sulfonium compounds. Some product is detected by vapor phase chromatography if an aliquot of the reaction solution is injected directly into the instrument without first quenching the reaction with acid indicating that higher temperatures are required before the reaction proceeds. Apparently, at 30°C, the radical anion of p-nitrobenzyltrimethylammonium bromide is stable and has no tendency to eliminate trimethylamine and thus partake in a free radical chain process to produce coupled product. Electron spin resonance experiments support this conclusion; irradiation of an ethanol solution of the ammonium salt with lithium-2-nitro-2-propyl anion results in a strong signal which is attributed to the radical anion of the ammonium salt (Figure 33). The apparent diminished intensity of the high-field nitrogen hyperfine splitting component results from line broadening and not radical decay.



$a_{NO_2}^{N} = 11.42$ gauss

$a_{\overset{+}{N}}^{N} = 2.22$ gauss

$a_{H_2}^{H} = a_{H_6}^{H} = 3.25$ gauss

$a_{H_3}^{H} = a_{H_5}^{H} = 1.01$ gauss

$a_{CH_2}^{H} = 1.40$ gauss

Admittedly, most of the experimental evidence assembled for the reaction of base with p-nitrobenzylsulfonium salts

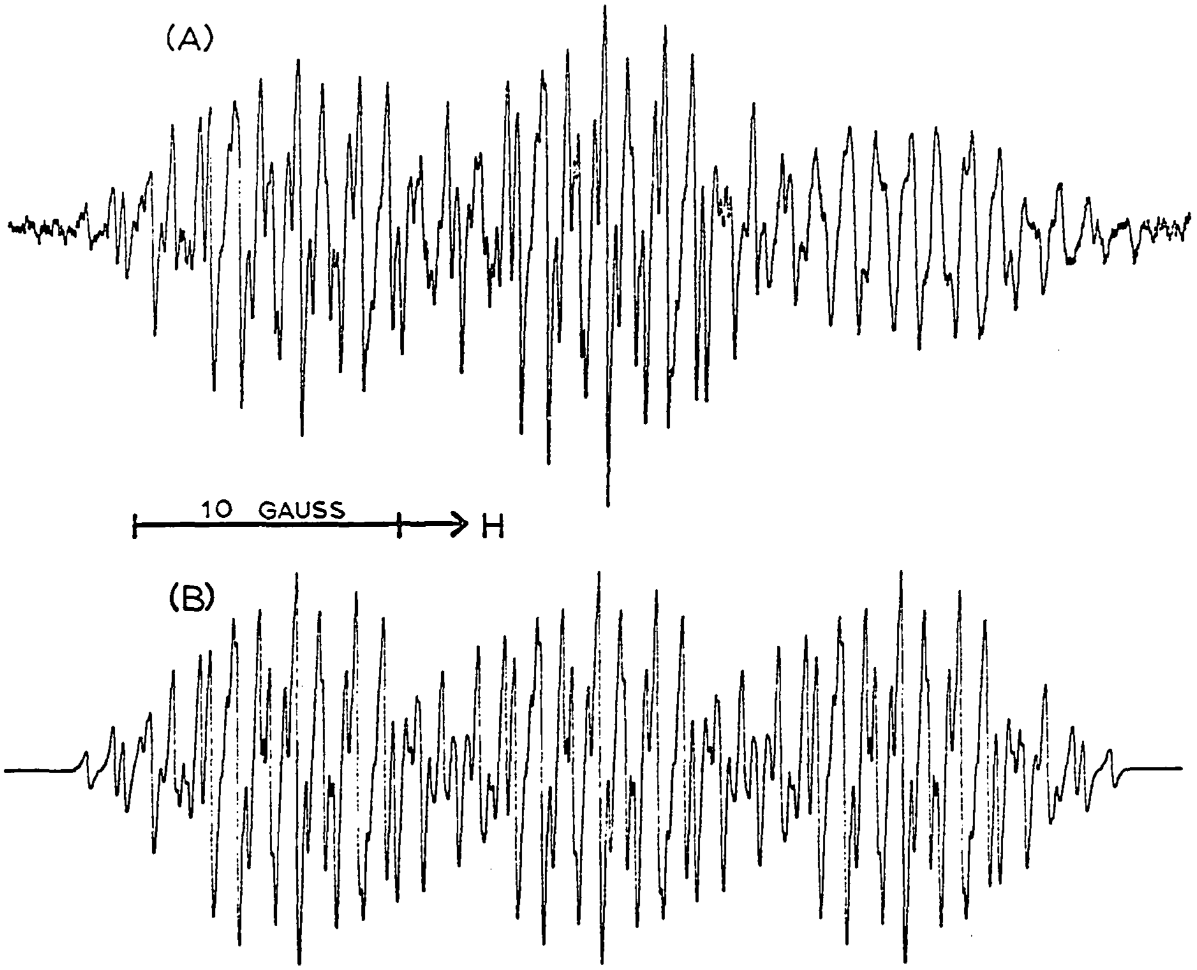
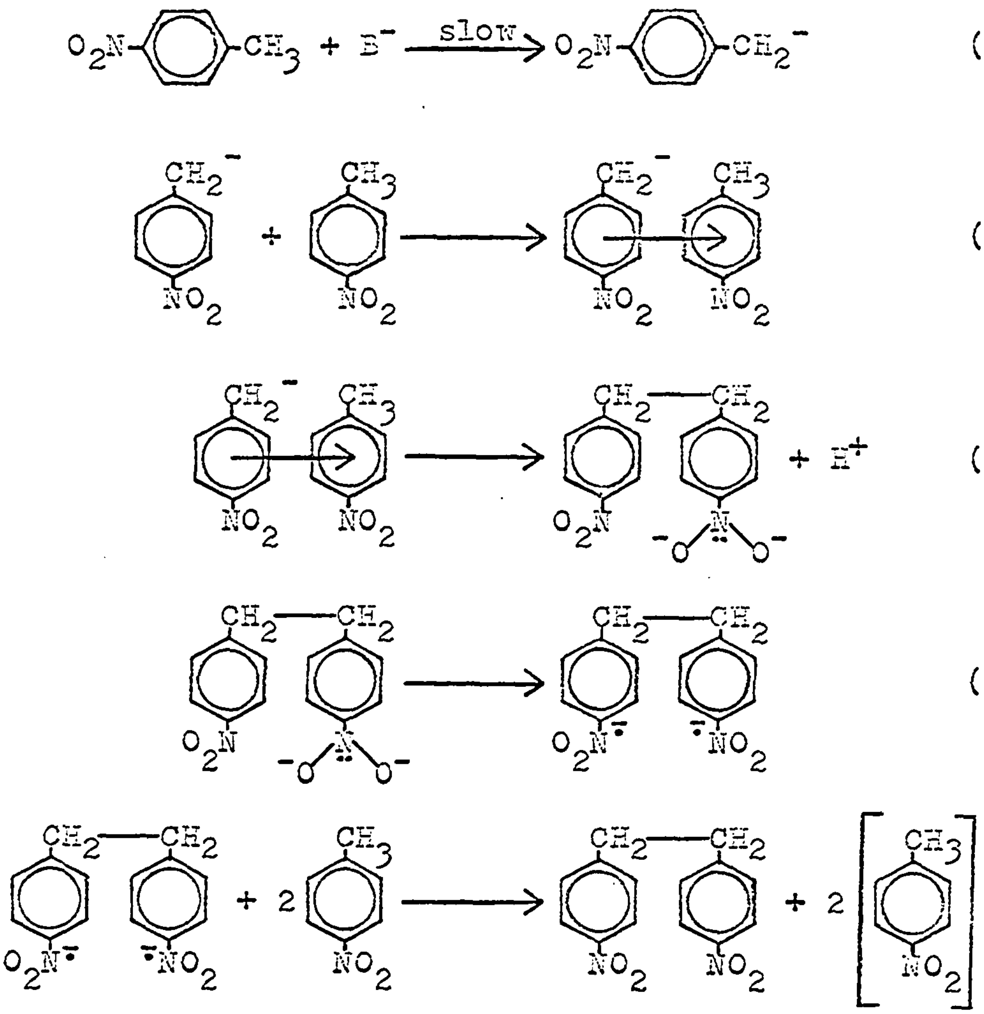


Figure 33. Electron spin resonance spectrum of the radical anion derived from irradiation of p-nitrobenzyltrimethylammonium bromide and the lithium salt of 2-nitropropane in ethanol

A. Experimentally obtained spectrum

B. Computer simulated spectrum; see text for assignments and values of hyperfine splitting constants does not support a free radical chain mechanism. However, in addition to the postulated carbene mechanism (62, 65, 66) another reaction pathway must be considered. Russell, *et al.* (74-76) have postulated the following mechanism for the formation of *p*,*p*'-dinitrobibenzyl from *p*-nitrotoluene in the presence of strong base:



(119)

(120)

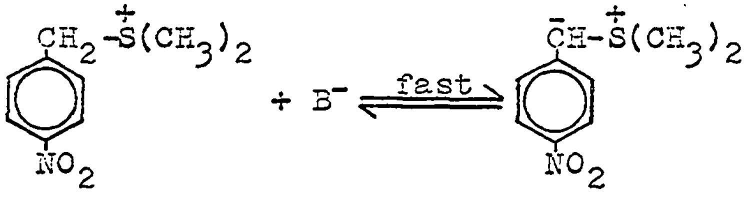
(121)

(122)

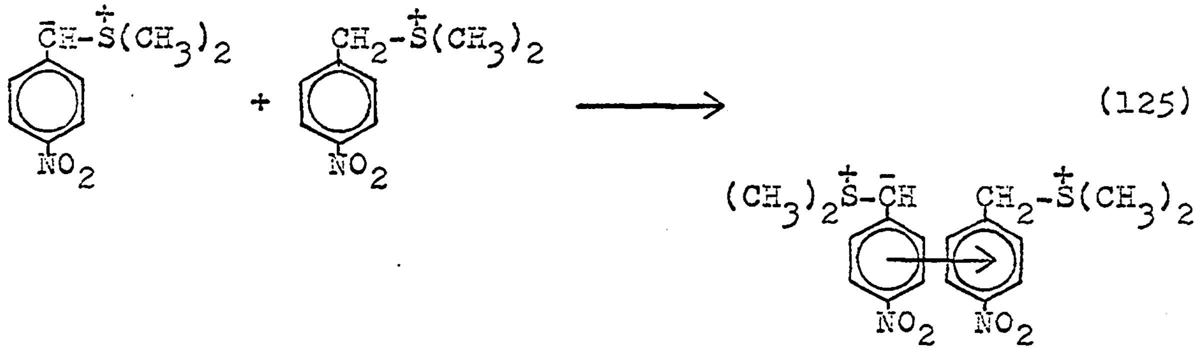
(123)

p,*p*'-Dinitrobibenzyl is formed even in the presence of oxygen, but as the oxygen pressure increased a larger fraction of the *p*-nitrotoluene is converted to *p*-nitrobenzoic acid. This suggests that *p*-nitrobenzyl radicals might be involved in the formation of the bibenzyl. However, attempts to intercept such radicals by conducting the reaction in the presence of other nitro-substituted carbanions, such as the 2-nitro-2-propyl anion or bis(2,4-dinitrophenyl)methide ion, failed (74). It will be recalled that in the reaction of *p*-nitrobenzyl chloride with the 2-nitro-2-propyl anion, evidence was obtained for the rapid coupling of the *p*-nitrobenzyl radical with the anion. Such a result eliminates the intermediacy of *p*-nitrobenzyl radicals in the reaction of *p*-nitrotoluene with strong base.

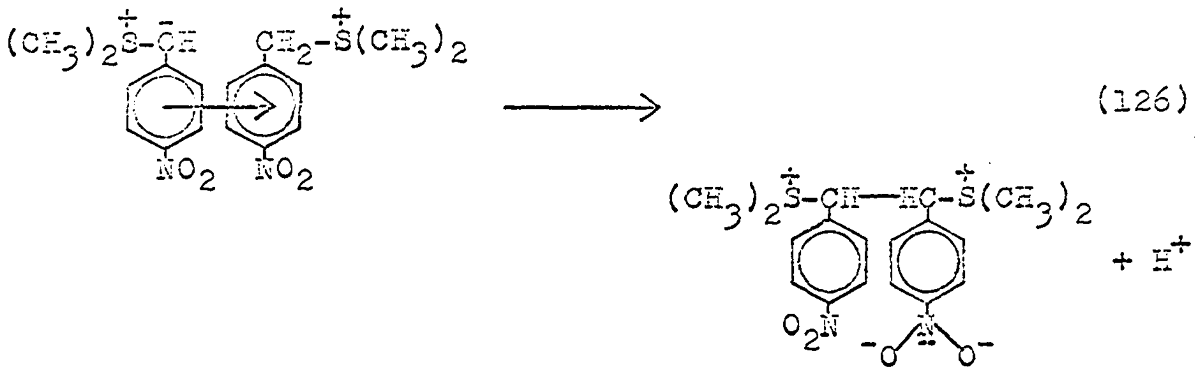
An analogous mechanism can be written for the formation of *p*,*p*'-dinitrostilbene from the *p*-nitrobenzylsulfonium salt in the presence of base:



(124)

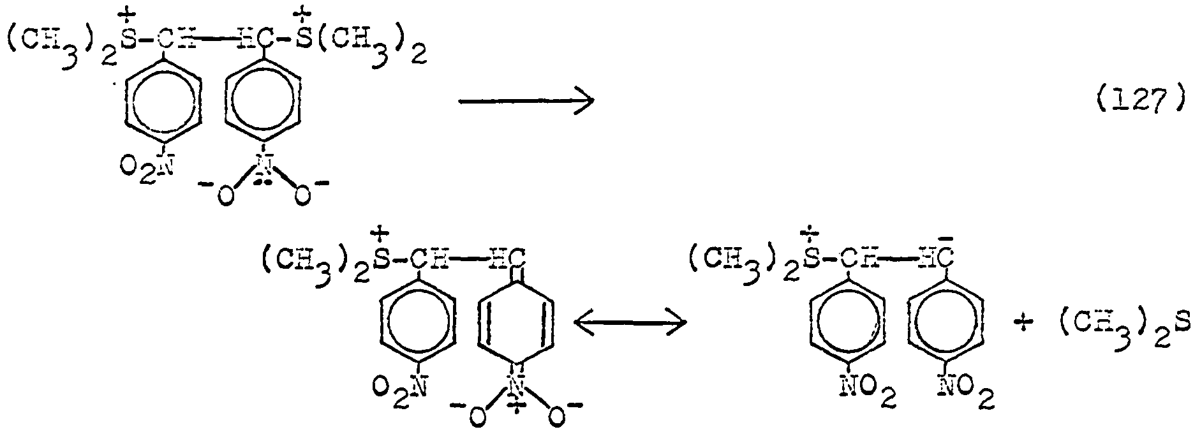


(125)

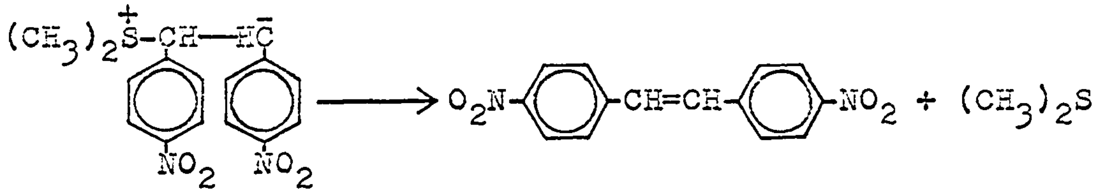


(126)

I

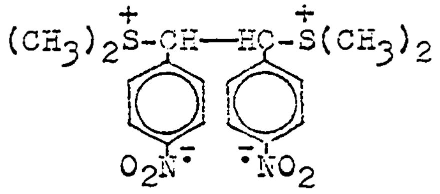


(127)



(128)

However, such a process does not appear feasible at least with pure water as solvent because of the low concentration of ylid and the fact that in water the reaction is first order in both hydroxide ion and sulfonium salt (62). Perhaps in a less highly solvating medium such as ethanol the reaction is of a different order. It is possible that two ylid molecules might react to produce intermediate I directly. An alternative mode of decomposition of I would be to undergo an intramolecular electron transfer to produce II. This diradical anion could

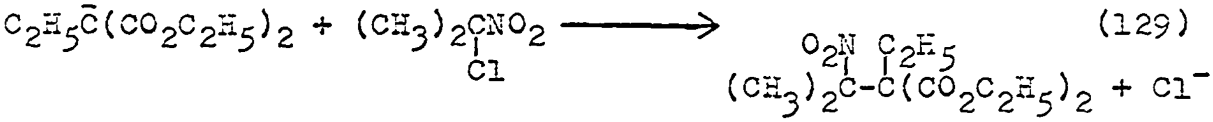


II

eliminate two molecules of dimethyl sulfide to form p,p'-dinitrostilbene.

E. Reaction of Various Anions with 2-Chloro-2-nitropropane

The reaction of the anion derived from ethyl malonic ester with 2-chloro-2-nitropropane has all of the characteristics of a free radical chain mechanism. Figure 34 shows that,



$$C_2H_5\bar{C}(CO_2C_2H_5)_2 + (CH_3)_2\underset{Cl}{\overset{}{\underset{|}{C}}}NO_2 \longrightarrow (CH_3)_2\overset{O_2N}{\overset{|}{C}}-\overset{C_2H_5}{\overset{|}{C}}(CO_2C_2H_5)_2 + Cl^- \qquad (129)$$

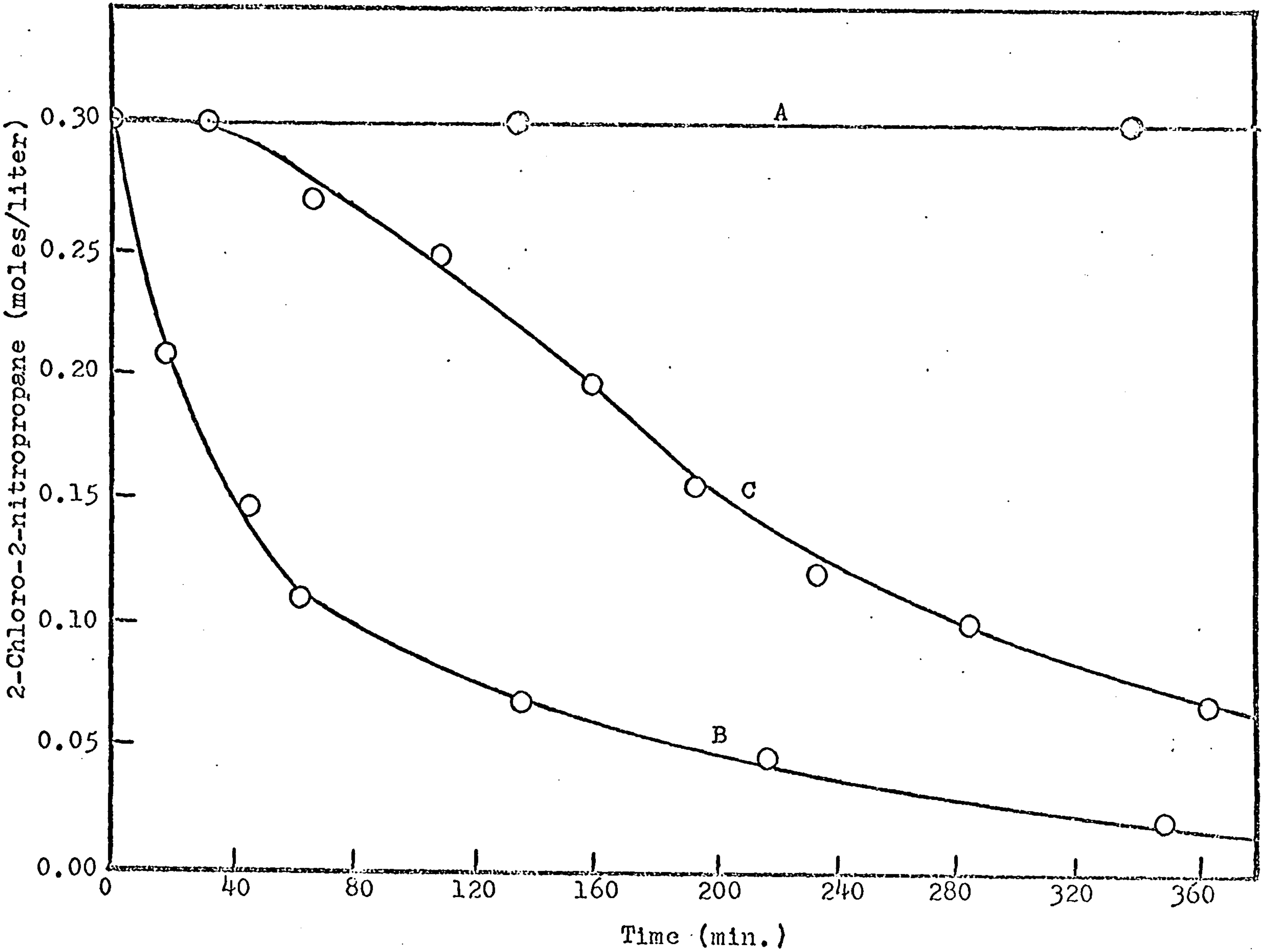
although there is no reaction in the dark for long periods of time, a fairly rapid consumption of chloro compound occurs when the reaction is irradiated. A small amount of p-dinitrobenzene has a pronounced inhibitory effect on the light reaction. These results demonstrate that this anion behaves similarly to the anion derived from 2-nitropropane in reaction with 2-chloro-2-nitro propane in ethanol. It is safe to assume that the same mechanism is operative in both reactions, namely, a free radical chain process involving the coupling of

Figure 34. Reaction of 0.60 M lithium salt of diethyl ethyl malonate with 0.30 M 2-chloro-2-nitropropane under nitrogen in ethanol at 30° C

A. Dark

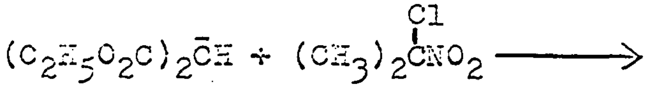
B. Illuminated

C. Illuminated in presence of 0.004 M p-dinitrobenzene


2-Chloro-2-nitropropane (moles/liter)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
40
80
120
160
200
240
280
320
360
Time (min.)
A
B
C

the 2-nitro-2-propyl radical with the corresponding carbanion. A preparative scale reaction of ethyl malonic ester anion with 2-chloro-2-nitropropane gave a moderate amount of the carbon alkylated product, 1-nitro-1-methylethyl ethyl malonic ester (reaction 129); boiling point 99-100°C at 0.33 mm (literature, 164°C at 14.0 mm--77). The proton magnetic resonance (p.m.r.) spectrum was in accord with the expected product.

The reaction of unsubstituted malonic ester anion with 2-chloro-2-nitropropane likewise is catalyzed by light and inhibited by *p*-dinitrobenzene. Virtually no reaction takes place in the dark. However, the simple carbon alkylated coupled product is not obtained but instead isopropylidene malonic ester is isolated in rather poor yield. This product undoubtedly results from the elimination of the elements of nitrous acid from the initially formed coupled product (77, 91):



$$(C_2H_5O_2C)_2\bar{C}H + (CH_3)_2\overset{Cl}{\overset{|}{C}}NO_2 \longrightarrow (C_2H_5O_2C)_2CH\text{-}C(CH_3)_2NO_2 + Cl^- \qquad (130)$$

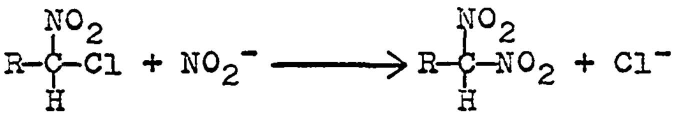
$$(C_2H_5O_2C)_2CHC(CH_3)_2NO_2 + B^- \longrightarrow (C_2H_5O_2C)_2C{=}C(CH_3)_2 + BH + NO_2^- \qquad (131)$$

The isopropylidene malonic ester was identified by its NMR and mass spectra (parent ion at 200).

The reaction of lithium thiophenoxide with 2-chloro-2-nitropropane also exhibits photolytic catalysis. But all attempts to isolate the expected product, 2-nitropropyl-2-thiophenyl ether, failed. The anions derived from ω-(methylsulfinyl)-acetophenone and ω,ω-diphenylacetophenone appeared to react with 2-chloro-2-nitropropane but only small amounts of unidentified oil were isolated from the reactions. However, the latter compound is known to photochemically decompose to 1,1,2,2-tetraphenylethane, benzaldehyde, and other products (78); such behavior accounts for the formation of an obvious mixture of products when the reaction of the anion with 2-chloro-2-nitropropane is irradiated. Phenyllithium reacted quite vigorously with the chloro compound to produce a small amount of biphenyl (17) and much polymeric material. No 2-nitro-2-phenylpropane was detected by vapor phase chromatography. Apparently, the phenyllithium reacted with the 2-chloro-2-nitropropane to produce 2-nitropropene which polymerized under the basic conditions (79). In any event, the expected coupled product probably could not be formed by a free radical chain process involving the coupling of 2-nitro-2-propyl radical with the phenyl anion since it has been demonstrated that the 2-nitro-2-phenylpropane radical anion is an unstable species (80).

The following compounds do not react with 2-chloro-2-nitropropane in ethanol at 30°C in either the light or dark: lithium salt of 2,6-dimethylphenol, lithium bromide, lithium nitrite, ammonium thiocyanate. No decrease in the concentration of chloro compound is observed for any of the anions even after reaction for many hours.

Hawthorne (81) has studied the mechanism of the ter Meer reaction (reaction 132) (82) and has postulated that the reaction proceeds through an isomerization of the reacting

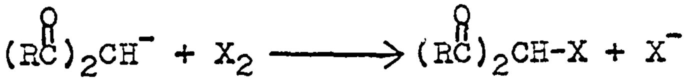


$$\mathrm{R{-}\underset{H}{\overset{NO_2}{C}}{-}Cl + NO_2^- \longrightarrow R{-}\underset{H}{\overset{NO_2}{C}}{-}NO_2 + Cl^-} \qquad (132)$$

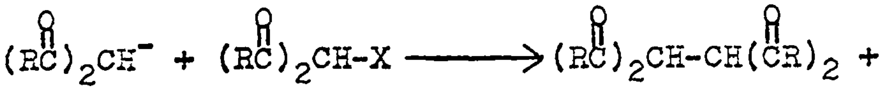
chloronitroalkane to its aci form followed by a nucleophilic displacement of chloride by nitrite ion. The reaction of 1-chloro-1-nitropropane with sodium nitrite in 50:50 ethanol: water was investigated and it was found that conducting the reaction in the presence of oxygen had no effect; no oxygen was aborbed and 1,1-dinitropropane was formed just as if the reaction had been performed under nitrogen. It can be concluded that free radicals are not intermediates in the ter Meer reaction.

F. Coupling of β-Dicarbonyl Compounds with Bromine or Iodine

The reaction of the anion derived from a β-dicarbonyl compound with either iodine or bromine is a common and useful method of preparing the dimer of the carbonyl compound (83, 84):



$$(R\overset{\overset{O}{\|}}{C})_2CH^- + X_2 \longrightarrow (R\overset{\overset{O}{\|}}{C})_2CH\text{-}X + X^- \qquad (133)$$



$$(R\overset{\overset{O}{\|}}{C})_2CH^- + (R\overset{\overset{O}{\|}}{C})_2CH\text{-}X \longrightarrow (R\overset{\overset{O}{\|}}{C})_2CH\text{-}CH(\overset{\overset{O}{\|}}{C}R)_2 + X^- \quad (134)$$

At the outset of this work it was thought that perhaps reaction 134 occured by way of an electron transfer process (reactions 3-5) rather than a simple displacement mechanism and the reaction of various β-dicarbonyl compounds with bromine and iodine was investigated.

It was shown that the reaction of the anion derived from acetylacetone with iodine in ethanol, ether, or tetrahydrofuran was not greatly affected by the presence or absence of molecular oxygen. The color due to iodine disappeared almost immediately upon mixing and only a very small amount of oxygen was consumed when the reaction was conducted on the oxidation apparatus.

Similar results were obtained for the couplings of diethyl malonate and ethyl acetoacetate with bromine in ethanol. It can be concluded that these coupling reactions do not involve free radical intermediates and probably occur via an S_N2 displacement process. The fact that substituted malonic esters do not readily couple under these conditions (39, 85) supports this conclusion since a substituted ester would be expected to react by an electron transfer process more readily than the unsubstituted compound.

The reaction of bromomalononitrile with potassium hydroxide in methanol at -78° C to produce the pentacyanopropenide ion (1) likewise was not influenced by the presence or absence of molecular oxygen. The rate of formation of product was monitored by observing the intensity of the absorption maxima at 3950 Å and 4130 Å and was virtually identical in both cases.

III. EXPERIMENTAL

A. Methods

The method of measuring the rate of oxygen uptake is a variation of the volumetric constant-pressure technique previously described by Janzen (86), Geels (87), and Bemis (88). The reactions are performed in a 125 ml creased flask equipped with a 10 ml addition flask which can be rotated, and a bubbler. The apparatus is pictured in Figure 35. In a typical reaction, the anion is dissolved in ethanol or formed *in situ* in the creased reaction flask by adding a known amount of standardized ethoxide solution to the acidic compound to be studied. The halogen compound is weighed out directly in the 10 ml addition flask and dissolved in a known amount of solvent. Sometimes, especially when the lithium salt of 2-nitropropane is employed as anion, the halogen compound is placed in the creased flask and the anion is dissolved in ethanol in the addition flask. The bubbler is then inserted into the reaction flask and the whole apparatus attached to a mechanical shaker (Figure 36). All joints are lightly greased with a high vacuum silicon lubricant. One end of a Tygon tube is attached to the bubbler, and the other end connected to a glass tube which, in turn, is connected to a mercury manometer, oxygen inlet, and burets equipped with a mercury leveling device. With this apparatus the pressure can be maintained at a constant value by raising or lowering the

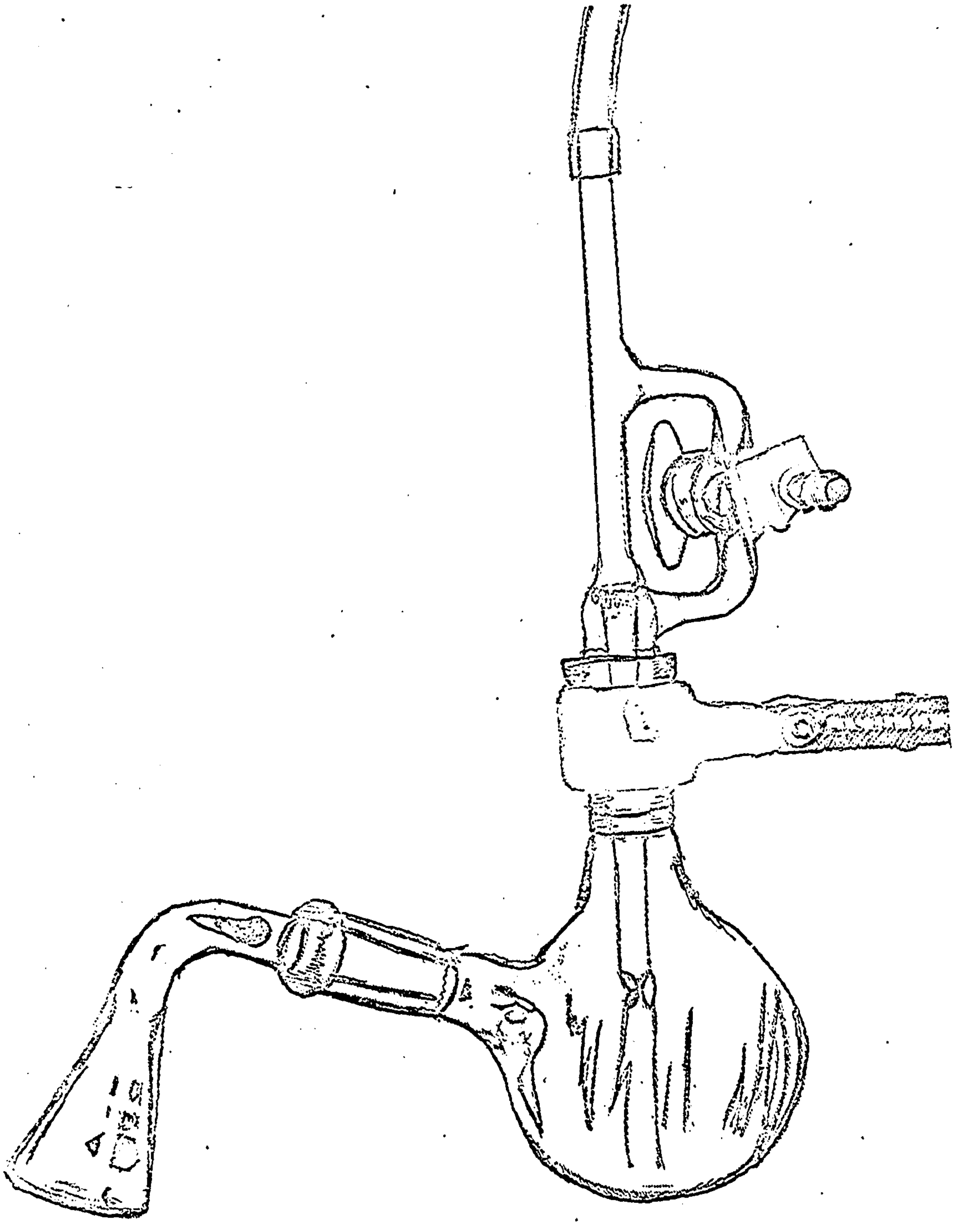
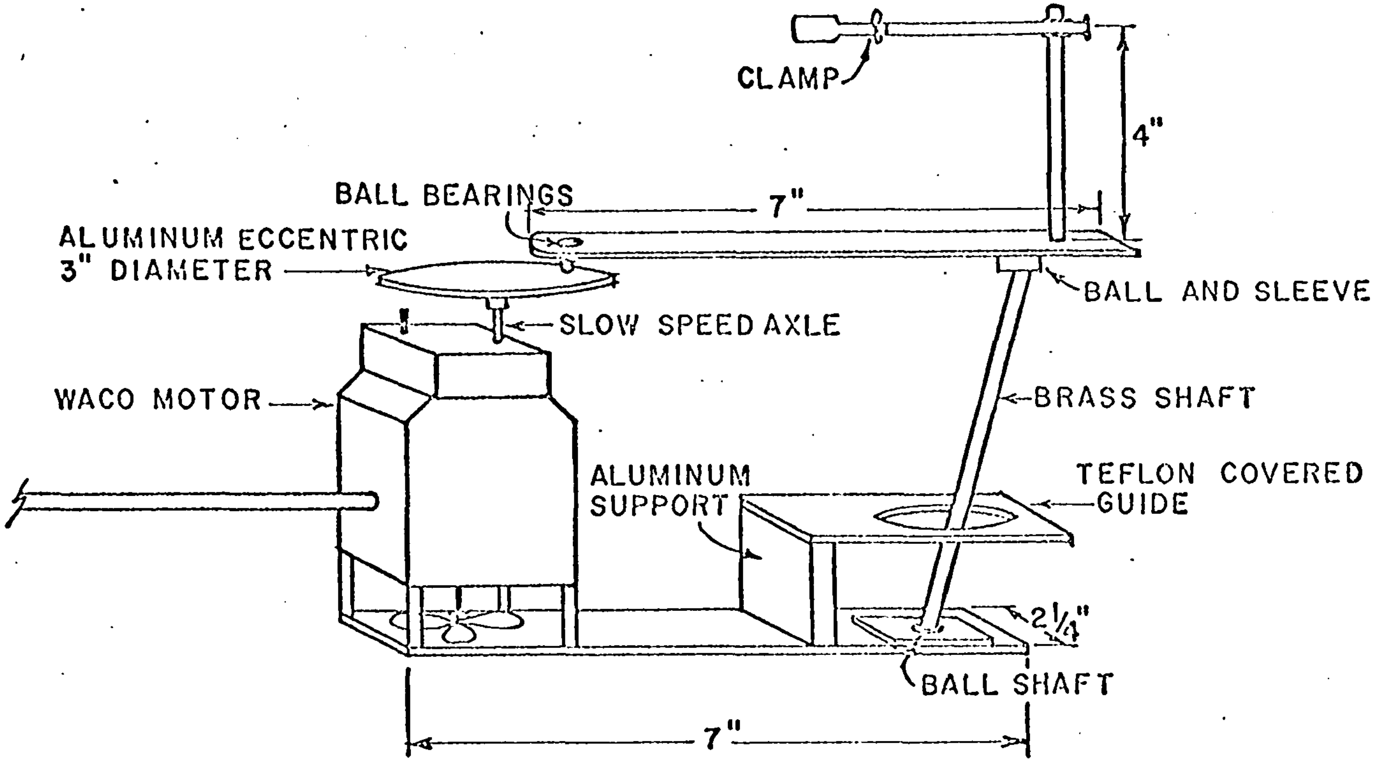


Figure 35. Oxidation apparatus consisting of creased flask, addition flask, and bubbler

Figure 36. Mechanical shaker used to agitate solutions for oxidation reactions

WRIST SHAKER



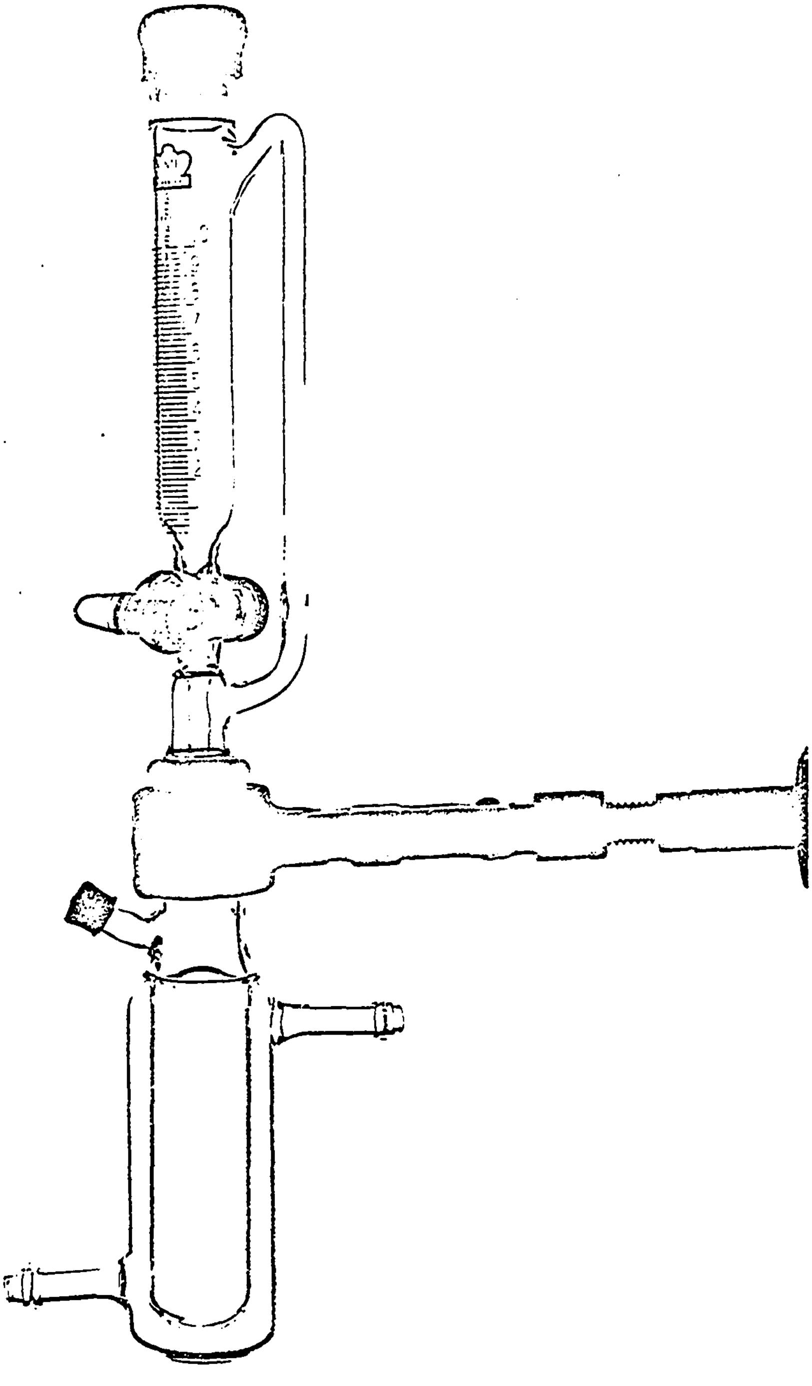
mercury leveling bulb on the buret and the change in volume measured. Pressure can be kept to within 1.00 mm of the desired constant value (usually 740 mm) and volumes read to the nearest 0.1 ml. Prior to beginning a reaction, oxygen is admitted to the system, the burets are purged by raising and lowering the mercury leveling bulb several times, and the solution saturated with oxygen by means of the bubbler. It was found that this was unnecessary; replacement of the bubbler with a simple ground glass joint and flushing of the reaction flask with oxygen was satisfactory. After purging with oxygen the burets are filled with oxygen and flow is stopped while simultaneously the three-way stopcock on the bubbler apparatus is turned to a position where the oxidation system is isolated from the air but oxygen can readily flow into the reaction flask from either the center tube or via the outside tube and stopcock. At time zero, the addition flask is inverted mixing the two reactants, the timer is started, and the mechanical wrist-shaker started.

The rate of oxidation is followed by raising the mercury leveling bulb to a point where the pressure equals the initial pressure, and then recording the time, volume, and temperature. A temperature correction is made by adding to the observed value a factor dependent upon the temperature change between the initial reading and subsequent readings. The temperature is recorded from a thermometer hung within several inches of the reaction flask. It was found that due to increased vapor pressure pure ethanol causes a 2.5 ml expansion per 1.0°C rise in the temperature. The temperature always increases during a reaction due to heat produced by irradiation and the mechanical shaker motor; thus, 0.25 ml was added to the observed value of oxygen absorbed for every 0.1 degree rise in the temperature. Although this correction factor is undoubtedly quite crude it is better than applying no correction at all. In most cases, the correction is usually only a small amount of the total value although in some instances of minimal oxygen absorption the correction is sizable.

For dark reactions the creased flask, the addition flask, and joint and part of the Tygon tubing are wrapped with black plastic electrical type to exclude all room light from the reaction. In irradiated experiments, a 275 watt General Electric sunlamp is positioned 18 inches from the reaction vessel. In order to minimize heating effects both the sunlamp and shaker are turned on prior to actually running the reaction so that a temperature equilibrium is reached.

Most of the irradiation experiments conducted under nitrogen were run in a jacketed Pyrex reaction vessel equipped with a 10 ml dropping funnel with sidearm and a 14/20 standard taper joint (Figure 37). The reaction chamber has a volume of approximately 20 ml and allows the use of a $\frac{1}{2}$ inch magnetic stirring bar. For reactions performed at 0°C, ethanol is circulated through a copper coil immersed in a water-ice-salt bath and then through the jacket surrounding

Figure 37. Jacketed Pyrex reaction vessel with addition funnel



the reaction chamber by means of a Haake Series F Constant Temperature Circulator (Poly Science Corporation). The temperature is determined by means of a thermometer fitted in a T-joint located in the Tygon tubing carrying the coolant at a distance of approximately 6 inches from the reaction vessel. The temperature can be controlled to 0° ± 1.0°C. For experiments performed at 12.5-13.0°C cold tap water is run through the outer jacket and for temperatures of 30°C or above the Haake Circulator with built-in heater is employed. The temperature can be controlled to ± 0.05°C with the latter. The sunlamp is positioned 10 inches from the reaction vessel.

A typical reaction is performed as follows. A known amount of halogen compound and solvent are placed in the reaction chamber. Likewise, a known amount of anion is dissolved in a known amount of solvent in the addition funnel, or the anion is generated _in situ_ using the appropriate base, solvent, and hydrocarbon. Both solutions are degassed for 30 minutes by bubbling prepurified nitrogen through hypodermic needles inserted through the rubber septums located atop the addition funnel and on the reaction chamber sidearm. After degassing, the circulator is started and the apparatus is allowed to equilibrate for approximately 15 minutes at the desired temperature. For reactions performed at 0°C the entire apparatus is immersed in an ice bath so the solution in the addition funnel is cooled also.

For irradiated experiments in which the rate of formation of product is to be monitored, the sunlamp is turned on prior to beginning the reaction. To start the reaction the stopcock on the addition funnel is opened and the timer is started. Aliquots (e.g., 0.40 ml) are removed by means of a 1.00 ml syringe through the rubber septum on the sidearm at various intervals and injected into a known small amount of concentrated nitric acid (e.g., 5-20 microliters) contained in 6 x 50 mm culture (test) tubes stoppered with rubber septums. The time is noted at the moment the reaction solution is quenched with the acid. Known amounts of these solutions are analyzed by gas-liquid partition chromatography (g.l.p.c.), the column employed and conditions used depending upon the compound to be monitored. In the reaction of the lithium salt of 2-nitropropane with p-nitrobenzyl chloride, p-nitrobenzyldimethylsulfonium bromide, or p-nitrobenzyltrimethylammonium bromide the carbon alkylated coupled product, 2-methyl-2-nitro-1-(p-nitrophenyl)propane. was detected on either a Perkin-Elmer Model 154 Vapor Fractometer with a 2 foot column of 20% GEXE-60 silicone gum nitrile on Chromosorb W at 200°C or an Aerograph A-350-B Dual Column Temperature Programmer Gas Chromatograph utilizing a 2 meter column of 3% SE-30 silicone gum rubber on Chromosorb P at 170°C. The amount of coupled product formed is determined by comparing the area of a peak with the area obtained from a standard solution of the coupled product in the same solvent. The areas of the peaks were determined by tracing with an Ott planimeter. Accuracy is probably only ± 5% but entirely satisfactory considering the results desired.

For irradiation experiments in which the decrease in concentration of the halogen compound is followed, a slightly different procedure is used. Instead of having the light directed onto the reaction vessel at the time of mixing the reaction solutions, the reaction apparatus is wrapped with aluminum foil to exclude all light. The stopcock is opened and the two solutions are thoroughly mixed after which time an aliquot is withdrawn for analysis by g.l.p.c. The aluminum foil is then removed and the irradiation by the sunlamp is begun. The whole procedure usually takes less than one minute to perform; the timer is started the moment irradiation of the reaction solution is begun. Since most of the reactions investigated are light catalyzed and proceed very slowly or not at all in the dark this first aliquot is considered the amount of halogen compound present at zero time. 2-Chloro-2-nitropropane is analyzed on the Perkin-Elmer instrument using a 2 meter diisodecyl phthalate column at 100°C; 2-bromo-2-nitropropane concentration is followed with the same column except at 125°C. The rate of reaction of p-nitrobenzyl chloride is determined by observing the decreasing areas on a 2 foot column of 20% GEXE-60 silicone gum nitrile on Chromosorb W held at 136°C. The amounts of halogen compound present in the various aliquots were determined by comparing subsequent peak areas to the area of the initial aliquot taken at zero time. An inert internal standard such as anisole or benzylphenyl ether was usually employed.

An alternative method of mixing the two reacting solutions is to remove the dropping funnel and to seal off the reaction flask with a rubber septum. The halogen compound is degassed in the reaction chamber as before but now the degassed anion solution is introduced with a syringe through the rubber septum. This technique is usually used when the reacting anion is the lithium salt of 2-nitropropane. A solution of the anion is made up by weighing the anion into a 10 ml Erlenmeyer flask, stoppering this with a rubber septum, flushing with nitrogen, and then adding previously degassed solvent. The resulting solution is then degassed an additional 5-10 minutes and a portion of this is drawn into a syringe for addition to the solution of halogen compound.

The dark reactions are performed in a manner identical to the above except that the reaction apparatus is thoroughly wrapped with several layers of aluminum foil for the duration of the experiment. For those reactions conducted at 0°C a small Erlenmeyer flask was usually used by sealing with a rubber septum and wrapping with either black plastic tape or aluminum foil and immersing in an ice bath. The reactants are introduced in a manner similar to that described above for the reaction assembly without the dropping funnel. Aliquots are taken as described earlier.

Ultraviolet and visible spectra were obtained on a Beckman DK-2A Ratio Recording Spectrometer. The following reactions were monitored by ultraviolet or visible spectroscopy: the reaction of the anion derived from 2-phenyl-1,3-indandione with diphenyliodonium salts by following the decrease with time of the concentration of the anion which has a characteristic absorption at 4520 Å; the reaction of p-nitrobenzyldimethylsulfonium bromide with aqueous base to produce p,p'-dinitrostilbene which absorbs at 3540 Å (difficulties encountered are discussed in the Results and Discussion section for this reaction); the ter Meer reaction in which absorbance at 3800 Å is observed due to the anion of 1,1-dinitropropane formed in the reaction of nitrite ion with 1-chloro-1-nitropropane. The photolyzed and dark reactions are conducted in the already described apparatus. Aliquots are removed with a syringe and simultaneously quenched and diluted to concentrations suitable for spectroscopic work. The change in concentration of reactant or product is determined by the relative change in optical density of the appropriate absorption maximum.

The reaction of p-nitrobenzyldimethylsulfonium bromide with sodium hydroxide was also followed by potentiometric titration. In a typical reaction 2.00 mmoles of the sulfonium salt is dissolved in 97.0 ml of solvent (ethanol-water mixtures in various ratios, see Results and Discussion section for this reaction) in a Pyrex immersion irradiation vessel and degassed with prepurified nitrogen for at least 30 minutes. Exactly 3.00 ml of 1.007 M sodium hydroxide is added and the timer is started at zero time. The sunlamp is directed towark the reaction vessel at a distance of 10 inches for photolyzed reactions and the vessel is wrapped in aluminum foil for dark reactions. Water is circulated through the outer jacket to maintain the desired constant temperature. By means of a syringe, 10.0 ml aliquots are removed at intervals and injected into 60.0 ml of 0.0065 M hydrochloric acid. The reaction is considered quenched and the time is noted when one half of the aliquot has been added to the acid solution. The resulting solution is then potentiometrically titrated with 0.0266 M sodium hydroxide solution using an automatic buret with 0.01 ml graduations. The pH of the solution is monitored during the titration with a Coleman Metrion pH Meter utilizing a glass electrode and a saturated calomel electrode. The point of maximum slope in a plot of pH versus added sodium hydroxide solution is taken as the end-point of the titration. It is found that this method gives very reproducible results.

The quantitative determination of acetone and nitrite ion resulting from the oxidation of the anion of 2-nitropropane in the presence of 2-bromo-2-nitropropane was performed as follows. 2-Nitropropane (0.92 g, 10.26 mmoles), potassium ethoxide solution (10.0 ml, 10.26 mmoles) and 2-bromo-2-nitropropane (1.72 g, 10.26 mmoles) and 10.0 ml ethanol were reacted in the oxidation apparatus as described earlier. The reaction absorbed 99.5 ml of oxygen at STP (4.44 mmoles). The reaction mixture was evaporated to dryness under vacuum at room temperature and the distillate containing the acetone and ethanol condensed in a dry ice trap. The distillate was then analyzed for acetone by a volumetric procedure based on reaction with hydroxylamine hydrochloride in an alcohol-pyridine solution (89). By this technique 8.15 mmoles of acetone was detected which corresponds to a yield of 79% based on 2-nitropropane and 92% based on oxygen consumed. This is in agreement with the observation that one mole of 2-nitro-2-propyl anion consumes one-half mole of oxygen and further illustrates that no 2-bromo-2-nitropropane is oxidized in the reaction.

The procedure followed for the determination of nitrite and nitrate ions is that of Russell (2). After performing the oxidation reaction as described above with the same amounts of reactants, the oxidized reaction mixture was evaporated to dryness at room temperature. The dry salts were quantitatively transfered to a 10.0 ml volumetric flask and dissolved in water. One ml of the solution was treated with 3.0 ml of saturated potassium permanganate solution and 1.0 ml of glacial acetic acid and warmed to 60°C for 5 minutes. The excess potassium permanganate was destroyed by the drop-wise addition of 30% hydrogen peroxide, the solution boiled for several minutes, cooled to 60°C, and 10 ml of nitron nitrate solution added (10 g nitron in 100 ml 5% acetic acid). The nitron nitrate was allowed to crystallize overnight in the dark; filtration yielded 0.3580 g (9.56 mmoles) of nitron nitrate. To 0.6 g of hydrazine sulfate in 15 ml of water at 50°C, 5 ml of the stack solution was slowly added with stirring. The solution was gently boiled for 2 minutes, cooled to 60°C, and 1 ml of glacial acetic acid and 10 ml of nitron reagent added; obtained 0.0656 g (0.35 mmole) of nitron nitrate. Thus the reaction of 10.26 mmoles of 2-nitropropane with 4.44 mmoles of oxygen produced 0.35 mmole of nitrate ion (3.4%) and 9.21 mmoles of nitrite ion (89% based on 2-nitropropane).

The electron spin resonance spectra shown in Figures 17 and 18 were obtained using a Varian V-4500 Spectrometer operating at ca. 9500 Mcps with a 9 inch magnet with Fieldial control and 100-kcps modulation; the spectrum shown in Figure 33 was obtained on a Varian E-3 Spectrometer. The samples were prepared using the inverted U-type mixing cell previously described (90) and a flat-fused silica "aqueous" sample cell and were thoroughly deoxygenated by bubbling prepurified nitrogen through them prior to mixing. Irradiation within the cavity was accomplished by directing the light from a 275 watt General Electric sunlamp through the irradiation slots in the cavity. The simulated spectra were computed on a JEOLCO Model JNM-RA-1 Spectrum Accumulator.

B. Solvents and Bases

Commerical absolute ethanol was refluxed with calcium hydride for 2 hours and then distilled, the first fraction and pot residue being discarded. The distillate was stored over molecular sieves in a Pyrex flask with closure by a ground glass stopper.

Dimethylformamide (Matheson, Coleman, and Bell) was dried over calcium hydride for 24 hours and then distilled twice under prepurified nitrogen at 12 mm pressure through a 30 cm Vigreaux column and stored over molecular sieves.

t-Butyl alcohol (Matheson, Coleman, and Bell) was purified by dissolving sodium metal in it and allowing it to reflux for 24 hours after which time it was fractionally distilled, the first fraction and a sizable pot residue being discarded. After repeating this procedure, the purified alcohol was stored over molecular sieves.

Lithium and potassium ethoxide solutions were prepared by adding a weighed amount of the cleaned metal to purified ethanol. The resulting solutions were titrated with standardized acid, and normalities obtained were consistent with that calculated on the basis of metal added. Potassium ethoxide solutions prepared in this way were stable for months, turning only slightly yellow; the lithium ethoxide solutions usually turned brown within a couple of weeks although the titer changed only gradually.

C. Chemicals

2-Nitropropane was practical grade from Eastman and was purified by distillation through a 90 cm Todd column packed with glass helices, the fraction boiling at 119.5-120°C at 740 mm was collected. G.l.p.c. and p.m.r. showed the distillate to contain only a very small amount of impurity of nitroethane. The distillation was repeated and pure 2-nitropropane was obtained.

The lithium salt of 2-nitropropane was prepared in solid form in the following manner. A lithium ethoxide solution was prepared by adding lithium metal (Lithium Co. of America, 0.70 g, 0.101 mole) to 100 ml of absolute alcohol. 2-Nitropropane (10.0 g, 0.112 mole) was added to the lithium ethoxide solution in a 1 l. round-bottom flask and the solution stripped down at room temperature on a rotatory evaporator. When the solution became viscous, but before precipitation of the salt began, 700-800 ml of anhydrous ether (Mallinckrodt) was added to cause precipitation. The resulting slurry was filtered and the precipitate washed with ether and subject to vacuum for 4 hours. It was then crushed and kept under oil-pump vacuum for an additional 24 hours.

2-Chloro-2-nitropropane was prepared as described in the literature (3) by bubbling chlorine gas into an alkaline solution of 2-nitropropane and distilling the oil which separated; b.p. 58-59°C at 60 mm, literature (3) 57°C at 50 mm.

G.l.p.c. and p.m.r. showed the 2-chloro-2-nitropropane to be free of any impurities.

2-Bromo-2-nitropropane was prepared in an analogous manner; b.p. 74-75°C at 56 mm, literature (3) 73-75°C at 50 mm. Both the chloro and bromo compounds are lackrymators and care should be exercised in their use.

Hexaphenylethane was prepared by a modification of literature procedures (92, 93). Triphenylchloromethane (Matheson, Coleman, and Bell, 30 g, 0.108 mole) was dissolved in 300 ml of acetone in a 500 ml round-bottom flask and thoroughly degassed. Mercury (80 g, 0.40 mole) was added and the flask was sealed with a glass stopper held securely in place with plastic tape and mounted on the mechanical shaker (Figure 36). The reaction flask was wrapped in aluminum foil to exclude all room light and allowed to shake for 8 hours. After reacting, the flask was opened and the contents filtered on a sintered glass disk in a nigrogen glove bag. The filtrate was then cooled to -78°C in a dry ice-acetone bath and the crystals of hexaphenylethane were collected by filtration in a nitrogen atmosphere. The product obtained by the above procedure is white but brief exposure to the atmosphere or light causes the hexaphenylethane to become yellow colored. The purity of the hexaphenylethane was determined by the amount of oxygen consumed by a weighed amount in toluene. When first prepared the product is 92% pure. The hexaphenylethane is best stored by dividing and sealing under nitrogen several lots in small vials with either wax or plastic tape. The vials are then wrapped with aluminum foil and stored in the freezer compartment of a refrigerator. By using this technique the hexaphenylethane can be stored for extended periods of time. The actual purity was determined immediately prior to its use as an inhibitor in the various reactions. Care was taken to assure that the hexaphenylethane was dissolved only in previously degassed solutions prior to reaction.

Diphenyliodonium chloride was prepared by adding a cooled acetic anhydride-sulfuric acid solution to a suspension of potassium iodate in a solution of acetic anhydride and benzene and working up as described in the literature (48).

Diphenyliodonium acetate was prepared by reacting diphenyliodonium chloride with silver acetate and recrystallizing the product obtained in this way from _t_-butyl alcohol and hexane containing a small amount of acetic acid (44).

Diphenyliodonium tosylate was obtained by reacting diphenyliodonium chloride with silver oxide and _p_-toluenesulfonic acid monohydrate in methanol in a manner similar to that described in the literature (94). This salt was used almost exclusively throughout this work because of its ready solubility in the various solvents.

2-Phenyl-1,3-indandione was formed by reacting phthalide and benzaldehyde in a solution of sodium ethoxide according to the method of Beringer (44).

p-Nitrobenzyldimethylsulfonium bromide was prepared by reacting *p*-nitrobenzyl bromide with an excess of dimethyl sulfide in acetonitrile in a manner analogous to that described in the literature for the preparation of *p*-nitrobenzylmethylisopropylsulfonium bromide (66). After precipitating the compound several times from methanol with ether, the *p*-nitrobenzyldimethylsulfonium bromide melted at 107-108°C. P.m.r. detected a small amount of methanol in the white product even after drying under vacuum for 24 hours. Most of the absorbed methanol was removed by stirring the salt with anhydrous ether for several hours, filtering, and drying.

p-Nitrobenzyltrimethylammonium bromide was prepared by the reaction of *p*-nitrobenzyl bromide with excess trimethylamine as reported in the literature (65).

Cis- and *trans*-*p*,*p*'-dinitrostilbene oxides were prepared for infrared and thin layer chromatography comparison purposes by the method described by Bergmann and Hervey (57).

Diethyl ethylmalonate was prepared from diethyl malonate and ethyl bromide in sodium ethoxide solution by a procedure similar to that described for diethyl *n*-butylmalonate (95). G.l.p.c. and p.m.r. showed the product to be pure.

ω,ω-Diphenylacetophenone was prepared by reacting desyl chloride, benzene and aluminum chloride by the procedure of Koelsch (96).

The remaining chemicals used in this work were commercially available and were purified by standard procedures when this was deemed necessary. The author wishes to thank Mr. E. T. Sabourin and Mr. L. A. Ochrymowicz for samples of ω-(methylsulfinyl)acetophenone.

IV. SUMMARY

It was shown in this work that the reaction of the lithium salt of 2-nitropropane with 2-halo-2-nitropropane or p-nitrobenzyl chloride is a free radical chain process involving the coupling of a radical with the 2-nitro-2-propyl anion as a key propagation step:

Initiation

$$R^- + R'X \longrightarrow R\cdot + R'X^{\overset{\cdot}{-}}$$

Propagation

$$R'X^{\overset{\cdot}{-}} \longrightarrow R'\cdot + X^-$$

$$R^- + R'\cdot \longrightarrow R\text{-}R'^{\overset{\cdot}{-}}$$

$$R\text{-}R'^{\overset{\cdot}{-}} + R'X \longrightarrow R\text{-}R' + R'X^{\overset{\cdot}{-}}$$

R^- = 2-nitro-2-propyl
$R'X$ = 2-chloro- or 2-bromo-2-nitropropane
p-nitrobenzyl chloride

The reaction was shown to be catalyzed by light and inhibited by free radical inhibitors such as oxygen, p-dinitrobenzene, and triphenylmethyl radicals.

In an attempt to determine the scope of the newly discovered mechanism it was shown that the anions derived from diethyl malonate and diethyl ethylmalonate can be substituted for the 2-nitro-2-propyl anion in reaction with 2-chloro-2-nitropropane. A variety of other anions were shown to be unreactive with 2-chloro-2-nitropropane under the reaction conditions usually employed.

The reaction of 2-phenyl-1,3-indandione with diphenyliodonium salts and the reaction of p-nitrobenzyldimethylsulfonium bromide with aqueous sodium hydroxide to produce p,p'-dinitrostilbene were also investigated in detail to determine if these reactions proceed by a chain mechanism analogous to that described above. No conclusive proof was obtained for a chain process and it was concluded that these reactions probably do not proceed in this manner. However, the reaction of the lithium salt of 2-nitropropane with p-nitrobenzyldimethylsulfonium bromide is a free radical chain process in which the p-nitrobenzyl radical couples with the 2-nitro-2-propyl anion.

It appears that the generality of the free radical chain mechanism described is limited mainly by the halogen-containing compound. This reactant must be sufficiently electronegative to accept an electron in a transfer process, but the resulting radical anion must be intrinsically unstable with respect to elimination of halide ion. In spite of this restriction, the interaction of a free radical with a carbanion is apparently an important reaction for the formation of carbon-carbon bonds.

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VI. ACKNOWLEDGMENTS

I wish to express my sincere thanks and appreciation to Professor Glen A. Russell for his guidance, encouragement, and patience during the course of this investigation. I especially appreciate the freedom of choice allowed me in choosing a research project and the provision of a first-year research assistantship. I am also very grateful to Professor Russell for his help and guidance in my quest for an academic appointment.

I thank the members of my committee for their time and effort in helping me to obtain an education. Special thanks are due to Professors O. L. Chapman and W. C. Wildman for helpful advice and letters of recommendation on several occasions and to Professor C. H. DePuy who first interested me in research. A note of thanks to the members of the Russell group for their friendship, useful comments and criticism, and experimental assistance is also in order.

Sincere and heartfelt thanks are due to my wife, Mary Ann, for her encouragement, understanding, and patience during the last three years and to my children, Angela and Christine, who have made sacrifices of which they are not even aware in order that this work could be completed.

I also want to thank my parents for a cherishable home life and for their encouragement and guidance throughout my education.

Finally, I wish to acknowledge the financial support provided by the National Institutes of Health in the form of a fellowship (award number 5-F1-GM-29, 259-03) from July, 1965 to September, 1967.