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Reactions of ceric ammonium nitrate with: I. Substituted phenylacetic acids, II. 2,5-Disubstituted furans, III. Olefins, IV. Substituted bibenzyls

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REACTIONS OF CERIC AMMONIUM NITRATE WITH:
I. SUBSTITUTED PHENYLACETIC ACIDS. II.
2,5-DISUBSTITUTED FURANS. III. OLEFINS.
IV. SUBSTITUTED BIBENZYLS.

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by

Darryl Wayne Brixius

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY
Department: Chemistry
Major: Organic Chemistry

Approved:

Signature was redacted for privacy.

In Charge of Major Work

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PART I

REACTIONS OF CERIC AMMONIUM NITRATE WITH SUBSTITUTED PHENYLACETIC ACIDS

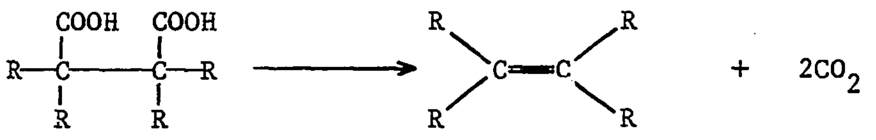
SUMMARY OF PART I

The mechanism of the oxidative decarboxylation of substituted phenyl acetic acids by cerium(IV) has been studied. It was concluded that the oxidation proceeds through a 1:1 acid-cerium(IV) complex, the decomposition of which is the rate determining step. The substituent effect upon this decomposition can be correlated by a Hammett $\rho\sigma$ treatment to give a ρ value of -2.92 ± 0.48 using σ^+ values.

While this value is larger than values obtained for other processes leading to a benzyl radical, trapping studies with oxygen have confirmed the intermediacy of a benzyl radical in the reaction. The high negative ρ value and good correlation with σ^+ values is interpreted to indicate considerable carbenium ion character at the benzylic carbon atom.

HISTORICAL

Although decarboxylations of carboxylic acids have been known for many years (1, 2) the oxidative decarboxylation of carboxylic acids has only recently come under extensive study. Much of this work has been concerned with the oxidative decarboxylation of 1,2-dicarboxylic acids



with lead tetraacetate (3), lead dioxide (4) or electrolytically (5, 6, 7) to the corresponding olefin.

Lead Tetraacetate (LTA)

The initial investigation of the oxidative decarboxylation of a monobasic carboxylic acid was undertaken by Kharash and coworkers (8) who studied the decomposition of LTA in acetic acid and compared the decomposition products to those obtained from the diacetyl peroxide decomposition under the same conditions. The authors postulate the formation of $\cdot CH_2COOH$ radicals initiating a radical chain process in the LTA decomposition.

In 1951, Mosher and Kehr (9) re-examined the decomposition of LTA in organic acids and rejected the radical mechanism in favor of the carbenium

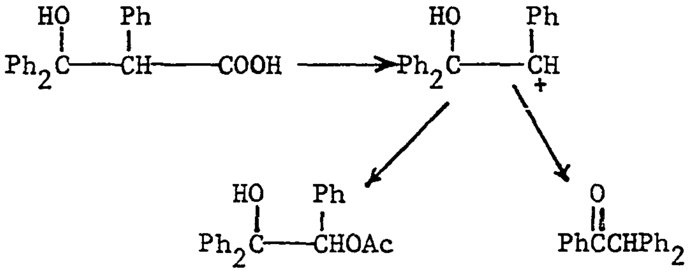
$$Pb(OAc)_4 + 4RCO_2H \rightleftharpoons Pb(OCOR)_4 + 4HOAC$$

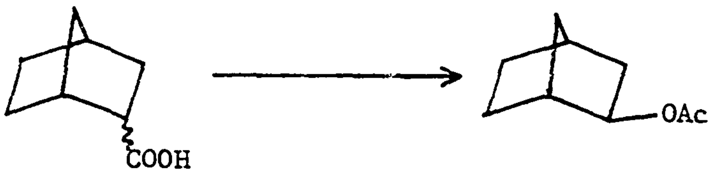
$$Pb(OCOR)_4 \longrightarrow Pb(COOR)_2 + RCO_2^- + RCO_2^+$$

$$RCO_2^+ \longrightarrow R^+ + CO_2$$

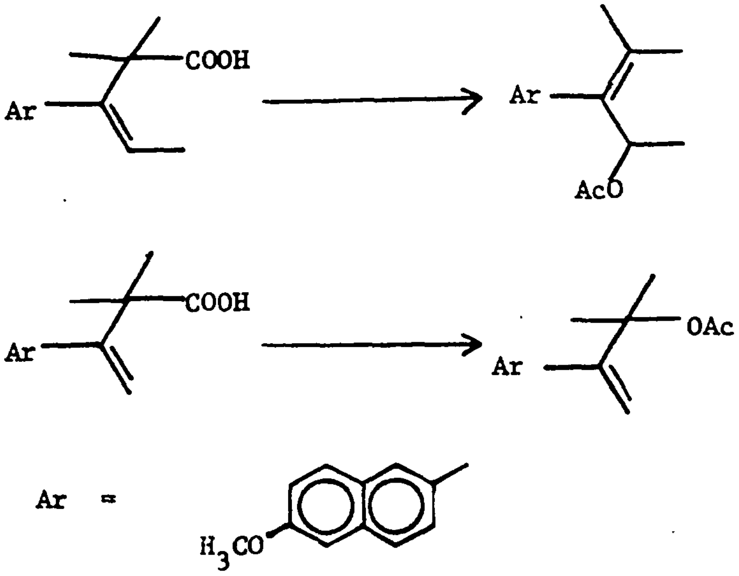
ion mechanism above. The support for this mechanism comes from the observation that the more stable the carbenium ion formed, the lower the temperature of which the decomposition occurs. In addition, there are no dimeric products formed. The products formed from the decomposition in pivalic acid are isobutylene, <u>tert</u>-butyl acetate and some 2-butene while in triphenylacetic acid the main product is triphenylmethyl acetate.

Corey and Casanova (10) have studied the oxidative decarboxylation of α, α, β-triphenyl-α-hydroxy propionic acid with LTA which yields predominantly phenyl benzhydryl ketone. Under similar conditions, optically active <u>exo</u> or <u>endo</u>-norbornane-2-carboxylic acids both provide <u>exo</u>-norbornyl acetate with the same degree of optical activity. The authors feel that these results are indicative of the formation of a carbonium ion as intermediate in both cases.





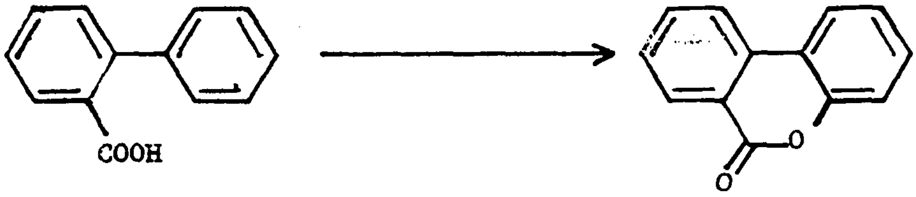
Jacques and coworkers (11) have studied the oxidation of unsaturated acids and write an ionic mechanism similar to Mosher's.



More recently, Kochi (12, 13, 14) and coworkers (15, 16, 17) have shown that the oxidative decarboxylation of aliphatic and α-aryl substituted aliphatic acids proceeds through a radical mechanism for LTA. The evidence for the radical nature of the decarboxylations was provided by the use of inhibitors, radical scavengers and esr spectroscopy. The mechanism of the LTA oxidations appears to be the same for both the photochemical and the thermal reaction. The LTA oxidation of

$$
\begin{aligned}
&\mathrm{Pb^{IV}(OOCR)_4} \longrightarrow \mathrm{Pb^{III}(OOCR)_3} + \mathrm{R\cdot} + \mathrm{CO_2} \quad \text{(initiation)}\\
&\mathrm{Pb^{III}(OOCR)_3} \longrightarrow \mathrm{Pb^{II}(OOCR)_2} + \mathrm{R\cdot} + \mathrm{CO_2} \quad \text{(propagation)}\\
&\mathrm{R\cdot} + \mathrm{Pb^{IV}(OOCR)_4} \longrightarrow \mathrm{Pb^{III}(OOCR)_3} + \mathrm{R^+}\\
&\mathrm{R\cdot} + \mathrm{Pb^{III}(OOCR)_3} \longrightarrow \mathrm{R^+} + \mathrm{Pb^{II}(OOCR)_2} \quad \text{(termination)}\\
&\mathrm{R\cdot} + \mathrm{HS} \longrightarrow \mathrm{RH} + \mathrm{S\cdot}
\end{aligned}
$$

biphenyl-2-carboxylic yields 3,4-benzocoumarin (18) while with



o-terphenyl-2-carboxylic acid, the reaction yields triphenylene. Both

mechanisms are thought to involve radical intermediates.

Davies and Waring (19) have studied the LTA oxidation of a series of 5-arylpentanoic acids in benzene under a nitrogen atmosphere to generate

1,2,3,4-tetrahydronaphthalenes. The formation of the naphthalenes was explained by formation of a radical by oxidative decarboxylation followed by intramolecular cyclization. Later Davies and Waring (20) oxidized phenylacetic acid and o-biphenylacetic acid and found acetate esters as products. It was postulated that the generation of the esters occurs from the decomposition of lead(IV) intermediates. It was felt that the generation of benzyl radicals was unlikely, since products unambiguously formed from radicals are found in low yield.

Shono and coworkers (21) have studied the reaction of cis and trans-2-phenylcyclopropane carboxylic acid with LTA. They propose that the acyloxonium ion proposed by Mosher is not involved as an intermediate, but a cyclopropyl radical was generated and oxidized to the cationic species.

Electrolytically

In 1968, Reidenbacher, et al. (22) electrolyzed alkyl carboxylates and postulated that the reaction proceeds through a carboxylate radical as the stability of the formed alkyl radical did not affect the rate of oxidation. Eberson (23) questioned Skell's work both on experimental and theoretical grounds.

Later, it was (24) determined that the electrolytic oxidation occurs through a carbenium ion intermediate but it could not be determined if an alkyl radical or a carboxylate radical was formed initially.

In the anodic oxidation of medium ring cycloalkane carboxylic acids, Traynham and Dehn (25) compared the products to those formed in solvolysis of halides or tosylates and decomposition of tosylhydrazones. In the oxidations, they find both <u>cis</u> and <u>trans</u> cycloalkenes as well as bicycloalkanes, but postulate that the carbenium ions formed in the anodic oxidation are unlike those formed in solvolysis or tosylhydrazone decomposition. Gassman and Zalar (26) have found similar results in the anodic oxidation of bicyclo[3.1.0]hexane carboxylic acids.

Recently, Coleman et al. (27) electrolytically oxidized a series of substituted phenylacetic acids. It was found that electron donating substituents lead to high yields of carbenium ion products while electron withdrawing substituents lead to good yields of coupled products. It was further postulated that these results indicate that the products observed could arise from two distinct pathways: 1) electron removal from the carboxylate group or 2) electron removal from the aryl group. Coleman and Eberson (28) later studied the anodic oxidation of the cesium salt of 9-methylanthracene-10-acetic acid and found that the reaction proceeded *via* electron removal from the aromatic nucleus.

Cobalt(III)

Clifford and Waters (29) studied the oxidation of a series of carboxylic acids with cobalt(III). The oxidation of phenylacetic acid was found to follow Michaelis-Menten kinetics, thus a rapid equilibrium was established. The products studied show that the products are derived entirely from free radicals. The authors postulate the following mechanism for the cobalt(III) oxidation of carboxylic acids. They further

$$RCO_2H + Co(H_2O)_6^{3+} \underset{k_2}{\overset{k_1}{\rightleftharpoons}} [R\cdot CO_2\cdot Co(H_2O)_5]^{2+} + H^+ + H_2O$$

$$RCO_2Co(H_2O)_5^{2+} \xrightarrow{k_2} R\cdot + CO_2 + Co^{2+} + 5H_2O$$

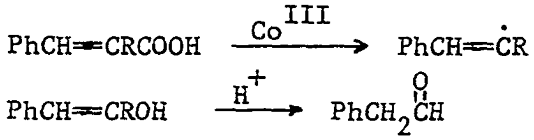
$$R\cdot + Co^{3+} \longrightarrow R^+ + Co^{2+}$$

$$R^+ + H_2O \longrightarrow ROH + H^+$$

state that the oxidation takes place by an inner sphere mechanism on cobalt.

Sharan and coworkers (30) have oxidized a series of acids of the type $Ph(CH_2)_nCOOH$ (n = 2-5) with cobaltic perchlorate and provide kinetic measurements and product analyses which substantiate the mechanism above. The organic radicals were trapped with bromoform to give the corresponding alkyl bromides. In the absence of a radical trap, hydrocarbons of the type $Ph(CH_2)_mCH_3$ were isolated when the higher acids are oxidized.

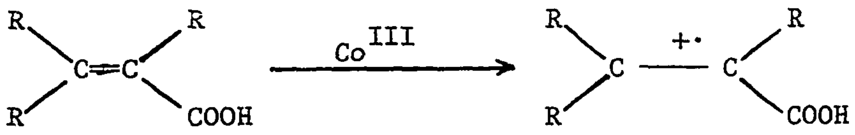
Later, Smith and Waters (31) oxidized unsaturated acids with cobalt(III) and from product studies postulate two concurrent mechanisms. The first is oxidative decarboxylation to yield the vinylic radical which leads to formation of an aldehyde or ketone.



$$PhCH{=}CRCOOH \xrightarrow{Co^{III}} PhCH{=}\dot{C}R$$

$$PhCH{=}CROH \xrightarrow{H^+} PhCH_2\overset{O}{\overset{\|}{C}}H$$

In this second pathway a direct attack on the double bond provides a radical cation which leads to rapid bond fission.



Starnes (32) has shown that aromatic carboxylic acids are oxidatively decarboxylated by cobalt(III). Catalytic amounts of cobalt are used in the presence of di-tert-butylperoxide, tert-butyl hydroperoxide or oxygen. The mechanism involves initial formation of acyloxy radicals, as indicated

$$\mathrm{ArCO_2H + Co^{3+} \longrightarrow ArCO_2\cdot + H^+ + Co^{2+}}$$
$$\mathrm{ArCO_2\cdot \longrightarrow Ar\cdot + CO_2}$$

by the formation of 3,4-benzocoumarin from oxidation of biphenyl-2-carboxylic acid, followed by decomposition to the phenyl radical.

Later, Lande and Kochi (33) studied the oxidative decarboxylation of cobalt(III) carboxylates and propose a radical mechanism similar to that postulated by Waters. Evidence for the intermediacy of a free radical is provided by radical trapping with copper(II) to yield the corresponding olifinic product.

Silver(II)

Anderson and Kochi (34) have studied the oxidative decarboxylation of aliphatic acids with a series of silver(II) complexes. It was proposed that the oxidation proceeds through two discrete equivalent oxidations. The first oxidation is of the carboxylate group to furnish an acyloxy

$$\mathrm{RCOOH + Ag^{II} \rightleftharpoons RCOOAg^{II} + H^+}$$
$$\mathrm{RCO_2Ag^{II} \longrightarrow RCO_2\cdot + Ag^{I}}$$

radical which eliminates carbon dioxide to give an alkyl radical which is

$$RCO_2\cdot \longrightarrow R\cdot + CO_2$$

$$R\cdot + Ag^{II} \longrightarrow R^+ + Ag^I$$

further oxidized by a second silver(II) species to the alkyl cation which leads to products.

The oxidative decarboxylation of aliphatic acids with peroxydisulfate has been found to be catalyzed by silver(II) by Anderson and Kochi (35). It was found that the rate of oxidation is first order in silver(II) and peroxydisulfate and zero order in carboxylic acid. The following mechanism was postulated. As can be seen, the actual decarboxylation step

$$Ag(I) + S_2O_8^{\ 2} \longrightarrow Ag(II) + SO_4^{\ 2-} + SO_4^{\ \overline{\cdot}}$$

$$Ag(I) + SO_4^{\ \overline{\cdot}} \longrightarrow Ag(II) + SO_4^{\ 2-}$$

$$Ag(II) + RCO_2H \longrightarrow Ag(I) + RCO_2\cdot + H^+$$

involves oxidation by silver(II) rather than by the peroxydisulfate. The presence of radical intermediates was indicated by copper(II) scavenging of the radicals to yield alkenes.

Manganese(III)

Anderson and Kochi (36) have also studied the oxidative decarboxylations of aliphatic acids by manganese(III). It was postulated that the reaction proceeds <u>via</u> two mechanistic pathways. The first, oxidative decarboxylation to generate the alkyl radical directly after complex formation. The

$$RCOOH + Mn(III) \rightleftharpoons RCOOMn(III) + H^+$$

$$RCOOMn(III) \longrightarrow R\cdot + CO_2 + Mn(II)$$

second, alkyl oxidation, is dependent upon the availability of α-hydrogen atoms for a given acid.

$$RCH_2COOH + Mn(III) \longrightarrow R\underset{\bullet}{C}HCOOH + Mn(II)$$

Manganese(III) acetate has also been found to oxidize phenylacetic acid by Van Helden and coworkers (37, 38) to yield products such as benzyl phenylacetate which are visualized as arising from free radicals.

Thallium(III)

The oxidative decarboxylation of carboxylic acids with thallium(III) was carried out by Bethea and Kochi (39) by photolysis in benzene. In these reactions, the tertiary, secondary and primary acids react to give different products at different irridiation wavelengths. These results were interpreted as an indication of the radical nature of the process, and the following mechanism was postulated.

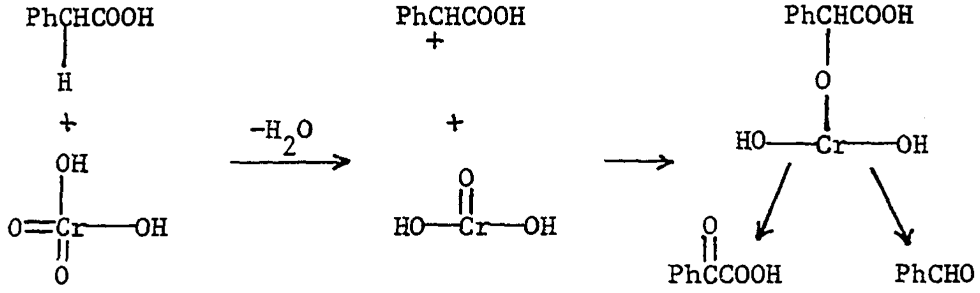
$$(RCO_2)_3Tl \xrightarrow{h\nu} (RCO_2)_2Tl(II) + R\cdot + CO_2$$

$$(RCO_2)_2Tl(II) \xrightarrow{fast} R\cdot + CO_2 + Tl(O_2CR)$$

The photolysis of phenylacetic acid at 2537Å provided a 300% yield of carbon dioxide along with reduction of thallium(III) to thallium(0).

Chromium(VI)

The oxidation of phenylacetic acid with chromium in acetic acid was found to be first order in both substrate and oxidant (40). It was further found that increasing the ionic strength increases the rate, which is consistent with the generation of charged species from neutral species. A mechanism was postulated which involves the abstraction of a hydride ion to generate a carbenium ion which is converted to a chromium ester followed by decomposition to products.



Cerium(IV)

Sheldon and Kochi (41) have studied the oxidative decarboxylation of a series of cerium carboxylates both photochemically and thermally. In the photochemical process, no rate difference was found when pivalic,

$$RCOOCe^{IV} \xrightarrow{h\nu} RCOO\cdot + Ce^{III}$$

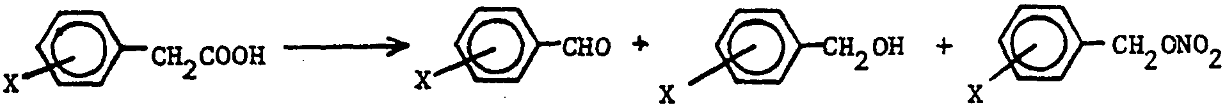
$$RCO_2\cdot \xrightarrow{fast} R\cdot + CO_2$$

isobutyric and n-butyric acids are oxidized. From these data it was concluded that the initial process involves formation of acyloxy radicals. In the thermal reaction, it was felt that the formation of the alkyl radical directly *via* a two bond cleavage was possible.

$$RCOOCe^{IV} \longrightarrow R\cdot + CO_2 + Ce^{III}$$

More recently, Mathai and Vasudevan (42) have undertaken the study of the cerium(IV) perchlorate oxidation of acetic acid. They found that the reaction is first order to cerium and close to first order in acetic acid. Evidence for a cerium-acetic acid complex was obtained both from spectrophotometry and from Michaelis-Menten reciprocal plots.

Recently, in this laboratory, the oxidation of substituted phenylacetic acids with cerium(IV) was found to yield substituted benzyl alcohols, substituted benzyl nitrates and substituted benzaldehydes.



The reaction was found to generate a Hammett correlation with $\rho = -3.01 \pm 0.31$ in 70% aqueous acetonitrile (0.35N nitric acid) (43). Evidence for the reaction proceeding through benzyl radical intermediates was obtained by trapping studies with oxygen (44).

Non-metal Oxidants

The oxidation of carboxylic acids and carboxylic acid salts by peroxydisulfate was initially studied by Fichter and coworkers (45, 46, 47, 48, 49). They found that the products from the anodic oxidation of aliphatic acids and the products from the peroxydisulfate oxidation were similar.

Later, Russell and Thomson (50) extended this work to aryl carboxylic acids and again found a similarity in the products formed. The following mechanism was postulated:

$$\mathrm{Ar\bar{C}OO} + \mathrm{SO_4^{-}\cdot}\ (\mathrm{OH\cdot}) \longrightarrow \mathrm{ArCOO\cdot} + \mathrm{SO_4^{=}}\ (\mathrm{OH^-})$$

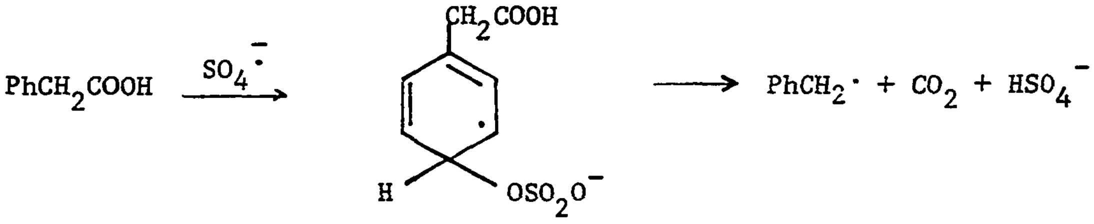
$$\mathrm{ArCOO\cdot} \longrightarrow \mathrm{Ar\cdot} + \mathrm{CO_2}$$

Brown and coworkers (51) later generated 3,4-benzocoumarins by the oxidation of o-phenylbenzoic acid with peroxydisulfate. The proposed mechanism for the reaction involves formation of an aryloxy radical followed by intramolecular cyclization.

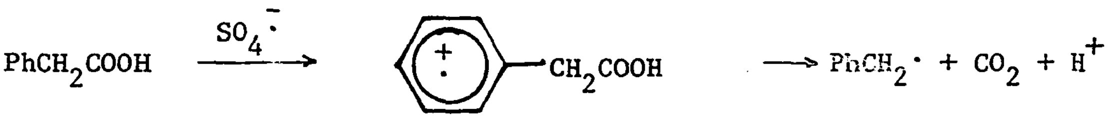
Recently, the peroxydisulfate oxidation of substituted phenylacetic acids was performed by Tanner and Osman (52). In this work, a ρ value of -0.436 was found when the rate data was correlated with σ^+. It was felt that this correlation indicates electron transfer from the carboxylate anion is concerted to some extent with loss of carbon dioxide in the rate determining step. An activated complex where resonance structure I is important was proposed to account for the correlation with σ^+.

$$ArCH_2CO_2^- \; SO_4^{-\cdot} \longleftrightarrow \underset{I}{ArCH_2\overset{+}{CO_2}\cdot} \; {}^-SO_4^{2-} \longleftrightarrow ArCH_2CO_2\cdot SO_4^{2-}$$

The oxidation of phenylacetic acid by the sulfate radical anion has been studied by Norman and coworkers (53). It was not possible to determine if the oxidative decarboxylation occurs by addition of the sulfate radical anion to the aromatic ring followed by fragmentation or by abstraction of an electron from the aromatic nucleus to form a radical



cation followed by fragmentation.



Norman and Storey (54) have also oxidized phenylacetic acid with the hydroxy radical and phenyl acetate anion with sulfate radical anion. In these cases the "addition in" of the radical species is preferred over the electron transfer from the carboxylate anion.

The oxidative decarboxylation of carboxylic acids by pyridine N-oxide has been studied by Cohen and coworkers (55, 56). It was found that the pyridine N-oxide is capable of a 4 electron oxidation of acids in the presence of acetic anhydride. A mechanism involving nucleophilic substitution of pyridine N-oxide for hydrogen at the α position of the acid and subsequent decomposition of this intermediate to benzaldehyde and phenylglyoxylic acid was envisioned.

RESULTS

The competitive oxidative decarboxylation of a series of substituted phenylacetic acids was carried out using a common procedure. The acids were accurately weighed into a flask and solvent was added. A ceric ammonium nitrate (CAN) solution in the same solvent was added and the mixture was heated at 80 ± 2° until the color of the solution had faded to pale yellow or decolorized. The mixture was then analyzed by nuclear magnetic resonance (nmr) spectroscopy. The results of these competitive oxidations are presented in Table 1.

Table 1. Relative rates of oxidation of substituted phenylacetic acids by CAN in 50% aqueous acetonitrile at 80°

Phenylacetic acid	k_X/k_H	log (k_X/k_H)
p-CH_3	20.43 ± 0.63[a]	1.310
m-CH_3	6.10 ± 0.08	0.785
H	1.00	0.000
p-Cl	1.14 ± 0.06	0.057
m-Cl	0.179 ± 0.00	-0.747

[a] Standard deviations based on at least 3 runs.

The values of log (k_X/k_H) (Table 1) were then plotted against constants for the substituents (Table 2). This plot appears in Figure 1.

A carbon dioxide analysis of the CAN oxidative decarboxylation of p-methylphenylacetic acid was performed. It had previously been shown (43) that in the oxidation of p-methylphenylacetic acid with 2.2 equivalents of CAN, only 80% of the acid had been oxidized. The results are presented

Table 2. Hammett values[a]

Substituent	σ^+
p-CH$_3$	-0.311
m-CH$_3$	-0.066
H	0.000
p-Cl	0.114
m-Cl	0.399

[a] Values obtained from reference (57).

Table 3. Carbon dioxide analysis of CAN oxidation of *p*-methylphenyl acetic acid at 55°

Run	mmoles CO$_2$ produced	% oxidation
1	3.18 ± 0.02	79.5 ± 0.5
2	3.25 ± 0.02	81.2 ± 0.5
3	3.11 ± 0.02	77.8 ± 0.5

in Table 3. The analysis was carried out using nitrogen as carrier gas and Ascarite as the carbon dioxide trap. Carbon dioxide produced was measured by weight difference of Ascarite trap immediately before and immediately after a run.

In an attempt to determine whether the oxidative decarboxylation of substituted phenylacetic acids by CAN proceeds through a radical intermediate, the oxidation of *p*-methylphenylacetic acid was carried out in the presence of oxygen.

Table 4. Radical trapping experiments for CAN oxidation of *p*-methylphenylacetic acid at 25° in 50% aqueous acetonitrile

Atmosphere	Products (mmoles)[a]		
	p-$CH_3C_6H_5CHO$	*p*-$CH_3C_6H_5CH_2OH$	*p*-$CH_3C_6H_5CH_2ONO_2$
nitrogen (1 atm.)	0.55	0.88	1.07
oxygen (1 atm.)	1.91	0.28	0.21

[a] Yields are based on two independent runs.

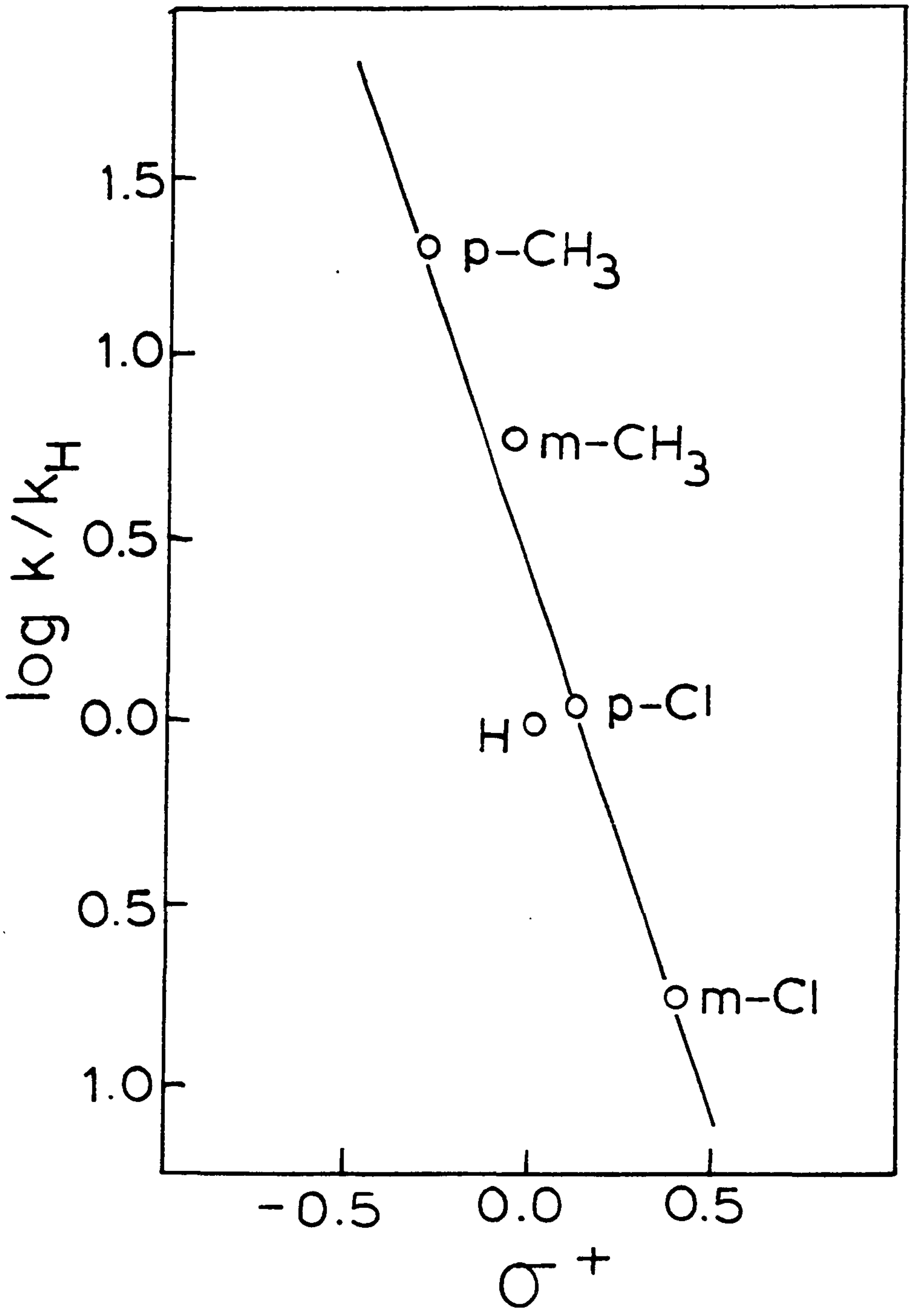
A competitive oxidation of *p*-methylphenylacetic acid *versus* phenyl acetic acid was performed employing an oxygen atmosphere for comparison with the previous competitive oxidations. This was used to determine if an oxygen species was responsible for the change in product distribution when oxygen was used as the radical trap. The results are presented in Table 5.

Table 5. Comparison of relative rates of CAN oxidation of *p*-methylphenyl acetic acid *versus* phenylacetic acid in 50% aqueous acetonitrile

Atmosphere	k_{CH_3}/k_H
air	20.43 ± 0.63[a]
oxygen	22.0 ± 1.1

[a] Relative rates are based on three independent runs.

Figure 1. Hammett plot (σ^+) for the CAN oxidation of substituted phenylacetic acids in 50% aqueous acetonitrile at 80°


log k / k$_H$
1.5
1.0
0.5
0.0
0.5
1.0
p-CH$_3$
m-CH$_3$
p-Cl
H
m-Cl
-0.5
0.0
0.5
σ$^+$

In other control experiments, benzyl alcohol was added to the reaction mixture of an oxidation of p-methylphenylacetic acid. Oxygen was bubbled through the reaction mixture during the oxidation. Comparison of the results from this oxidation with the radical trapping experiment is shown in Table 6. The reduction in the total yield of products from the acid is 0.50 mmoles while the yield of benzaldehyde from the benzyl alcohol oxidation is 0.56 mmoles.

Table 6. Oxidation of p-tolylacetic acid with CAN in the presence and absence of benzyl alcohol employing an oxygen atmosphere

Benzyl alcohol (mmoles)	Products (mmoles)				
	p-TolCH_2CHO	p-TolCH_2OH	p-TolCH_2ONO_2	PhCHO	PhCH_2OH
0.00	1.91	0.28	0.21		
1.00	1.51	0.18	0.21	0.56	0.43

A final control experiment involved using a cerium(III) (cerium(IV) reduced with pinacol) solution with added p-methylbenzyl nitrate. Oxygen was bubbled through the solution for the same period of time as the oxidative decarboxylation of p-methylphenylacetic acid. The reaction mixture was worked up identically to the work-up for the oxidative decarboxylations. The analysis of the residue was performed by nmr and showed 0.58 mmoles p-methylbenzyl nitrate and 0.30 p-methylbenzyl alcohol from an initial concentration of 0.95 mmole of p-methylbenzyl nitrate.

DISCUSSION

General Considerations

Cerium(IV) Oxidant Species

Beineke (58) has determined that the structure of solid ceric ammonium nitrate (CAN) has 6 bidentate nitrates coordinated to a central cerium atom. The complex has a center of symmetry with the nitrates as blades of two 3-bladed propellers. From a study of the ir and raman spectra of aqueous CAN, Miller and Irish (59) have concluded that a minimum of 3 nitrates are coordinated to each cerium. Henshall (60) has determined that tetranitratocerium(IV) is the predominant species in glacial acetic acid solutions of CAN. Larsen and Brown (61) have found evidence for 12 cerium oxygen interactions from X-ray diffraction studies of aqueous CAN solutions.

Mechanistic Approaches

The oxidation of an acid by a metal ion may be considered to proceed through a complex. As there is evidence that cerium(IV) (42) does form complexes with carboxylic acids, the competitive oxidation of two acids A_1 and A_2 by cerium(IV) may be represented by:

$$A_1 + Ce(IV) \overset{K_1}{\rightleftharpoons} C_1 \xrightarrow{k_1} P_1$$

$$A_2 + Ce(IV) \overset{K_2}{\rightleftharpoons} C_2 \xrightarrow{k_2} P_2$$

where C_1 and C_2 are the complexes and P_1 and P_2 are the products. The following derivation gives an expression for the relative rates of oxidation of A_1 and A_2.

Now,

$$K_1 = \frac{(C_1)}{(A_1)(Ce^{IV})} \qquad (1)$$

and

$$(A)_T = (A_1) + (C_1) \qquad (2)$$

where $(A)_T$ is the total A_1 at any time.

Now,

$$K_1 = \frac{(C_1)}{(Ce^{IV})(A_T - C_1)} \qquad (3)$$

and

$$\frac{dP_1}{dt} = -\frac{dA_1}{dt} = k_1(C_1) = k_1\left[\frac{K_1(Ce^{IV})(A_1)_T}{1 + K_1(Ce^{IV})}\right] \qquad (4)$$

Similarly

$$\frac{dP_2}{dt} = -\frac{dA_2}{dt} = k_2(C_2) = k_2\left[\frac{K_2(Ce^{IV})(A_2)_T}{1 + K_2(Ce^{IV})}\right] \qquad (5)$$

Now, dividing (4) by (5)

$$\frac{dA_1}{dA_2} = \frac{k_1\left[\dfrac{K_1(Ce^{IV})(A_1)_T}{1 + K_1(Ce^{IV})}\right]}{k_2\left[\dfrac{K_2(Ce^{IV})(A_2)_T}{1 + K_2(Ce^{IV})}\right]} \qquad (6)$$

or, rearranging

$$\frac{dA_1}{dA_2} = \frac{k_1}{k_2}\left[\frac{K_1(Ce^{IV})(A_1)_T}{K_2(Ce^{IV})(A_2)_T}\right]\left[\frac{1 + K_2(Ce^{IV})}{1 + K_1(Ce^{IV})}\right] \qquad (7)$$

Now, if $K_1 = K_2$, the equation reduces to

$$\frac{dA_1}{dA_2} = \frac{k_1(A_1)_T}{k_2(A_2)_T} \qquad (8)$$

or

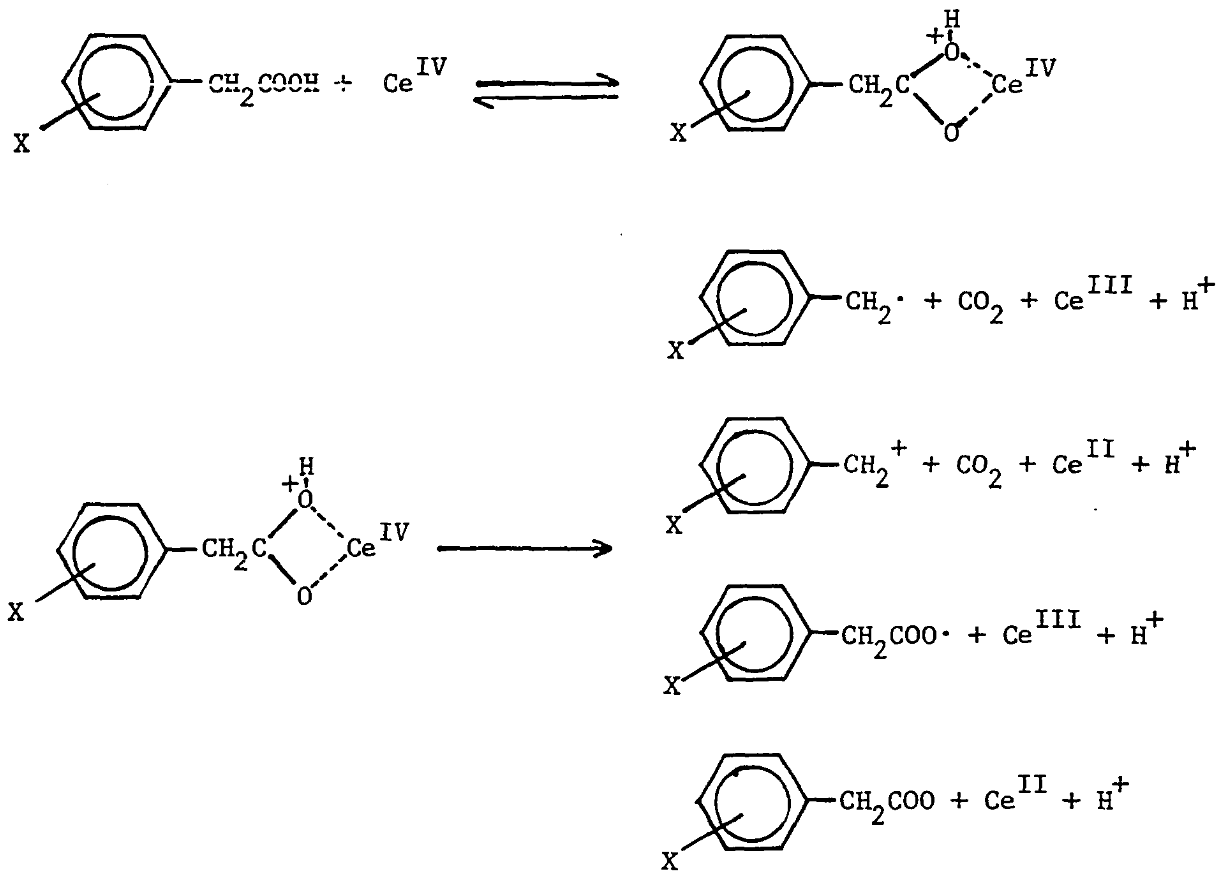
$$\frac{k_1}{k_2} = \frac{dA_1/(A_1)_T}{dA_2/(A_2)_T} \tag{9}$$

which, upon integrating from 0 to t gives

$$\frac{k_1}{k_2} = \frac{\ln\left[(A_1)_T\right]_o - \ln\left[(A_1)_T\right]_t}{\ln\left[(A_2)_T\right]_o - \ln\left[(A_2)_T\right]_t} \tag{10}$$

Now, k_1/k_2 is a measure of the rate of decomposition of the complexes C_1 and C_2 and the validity of equation (10) derived above depends upon the assumption that $K_1 = K_2$. Substituted phenylacetic acids were chosen for the competitive oxidations such that this assumption is reasonable. Support for this assumption is found in the fact that the pK_a values for substituted phenylacetic acids range from 3.92 for p-nitrophenylacetic acid to 4.36 for p-methoxy and p-methylphenylacetic acids (62). In addition, Smith and Waters (31) have determined that the equilibrium constants for complex formation in the oxidation of propionic acid and phenylacetic acid by cobalt(III) are essentially the same.

Thus, using substituted phenylacetic acids as substrates, the generalized oxidation mechanism can be rewritten as shown in Scheme 1. The assumption that the complex equilibrium is a fast step is reasonable in light of the work of Mathai and Vasudevan (42) in which it was found that the cerium(IV) perchlorate oxidation of acetic acid follows Michaelis-Menten kinetics. A Hammett $\rho\sigma$ correlation for the decomposition of the complex would give a ρ value for the substituent effect on the oxidation. When the competitive oxidations were carried out and the Hammett correlation applied, the following ρ values were obtained.



Scheme 1. Generalized mechanism for the oxidative decarboxylation of substituted phenylacetic acids by cerium(IV)

Table 7. Hammett ρ values for the CAN oxidation of substituted phenylacetic acids at 80°

Solvent	σ^+ values	ρ^+
70% aqueous acetonitrile[a] ($0.35\ N\ HNO_3$)	–[b]	-3.01 ± 0.31
70% aqueous acetonitrile[a] ($0.35\ N\ HNO_3$)	–[c]	-2.86 ± 0.41
50% aqueous acetonitrile	–[c]	-3.30 ± 0.60
50% aqueous acetonitrile	–[d]	-2.92 ± 0.48

[a] Obtained from reference (43).

[b] σ^+ values obtained from reference (63).

[c] σ^+ values obtained from reference (64).

[d] σ^+ values obtained from reference (57).

These values are in good agreement for the two solvent systems which would be expected from the work of Nave (65) where it was found that no change in the ρ value for the oxidation of alcohols by CAN occurred when the solvent system was changed from 75% aqueous acetonitrile to 85% acetic acid.

The ρ values obtained from the substituted phenylacetic acid oxidation by CAN, however, are somewhat unusual. The ρ value for most processes leading to a benzyl radical is -0.7 to -1.5 (66, 67, 68, 69, 70) while the ρ value for processes leading to benzyl cations is usually in the range of -4.5 to -6.7 (63, 71, 72, 73, 74). Thus, the values for the oxidative decarboxylation of substituted phenylacetic acids by CAN fall between these two ρ value ranges. Nave (65) has also reported a ρ value for the oxidation of 2-aryl-1-phenylethanols by cerium(IV) of -2.00. The oxidation was shown to proceed through radical intermediates by trapping studies.

The large negative ρ value for the oxidative decarboxylation of substituted phenylacetic acids by CAN would seem to eliminate the formation of either a carboxylate radical or a carboxylate cation in the rate determining step since the substituent effect for either of these processes should be small as indicated by the small change in pK_a values for the substituted phenylacetic acids (62). Therefore, the formation of either a benzyl radical or benzyl cation in the rate determining step must be considered. Since the ρ value obtained from the competitive oxidations does not allow for the distinction between these two possibilities, another method was attempted.

Radical Trapping Experiments

As cerium(IV) is a known one electron oxidant (75), the formation of a benzyl radical rather than a benzyl cation in the rate determining step of the oxidative decarboxylation of substituted phenylacetic acids by CAN is reasonable. In order to establish that the oxidation does proceed through a radical intermediate, the oxidation of p-methylphenylacetic acid was carried out in the presence of oxygen. The reaction mixture was analyzed by nmr and the yield of products determined (Table 4). It was shown that when oxygen is bubbled through the reaction mixture, the yield of p-methylbenzaldehyde is increased four-fold while the yield of benzyl nitrate is decreased four-fold. The increase in the yield of aldehyde is consistent with the trapping of an intermediate p-methylbenzyl radical with oxygen to yield a p-methylbenzylperoxy radical which undergoes subsequent decomposition (76).

Control Experiments

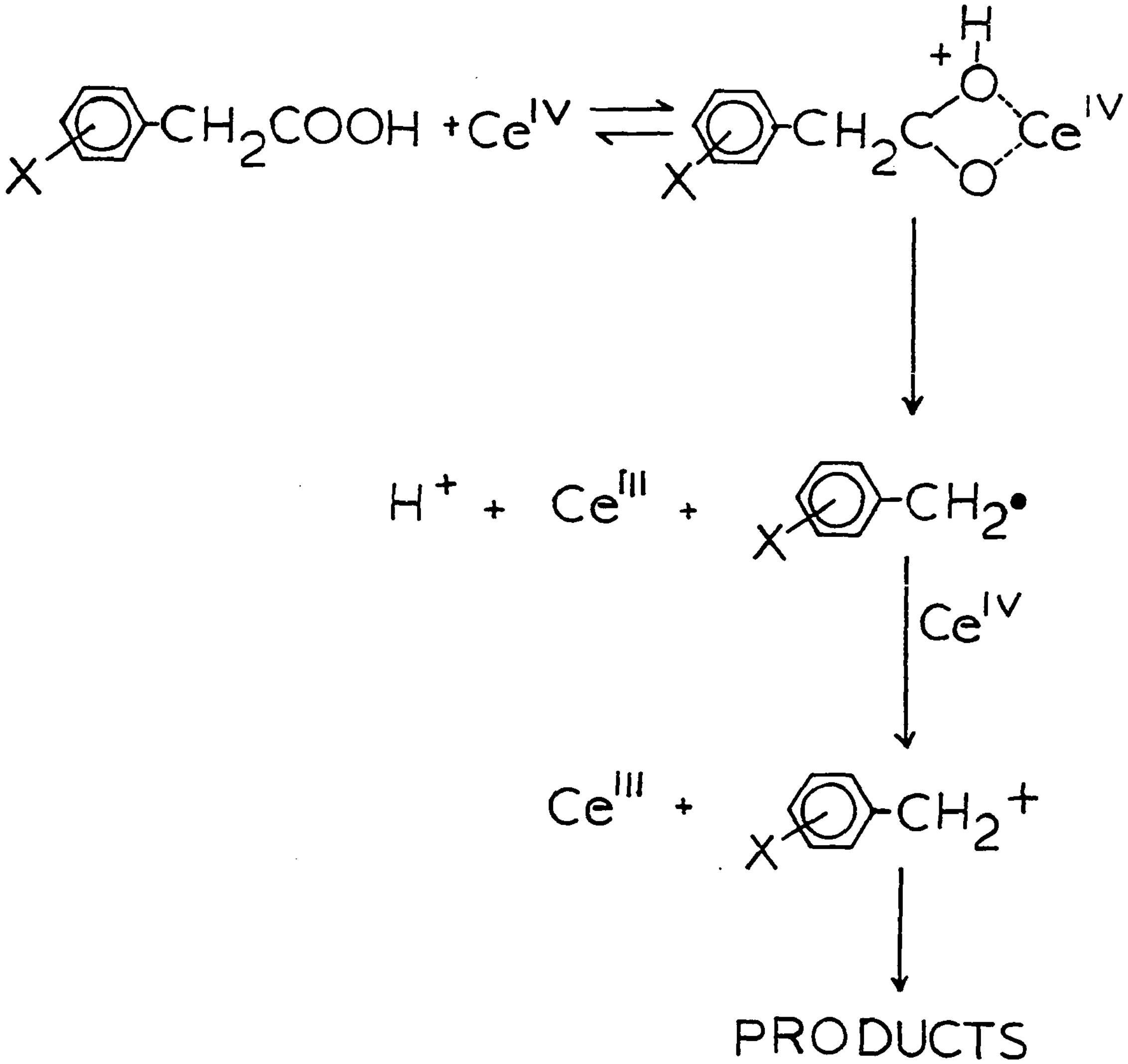
A series of control experiments were carried out to eliminate the possibility of the oxidation of the substituted phenylacetic acids occurring through a cerium-oxygen complex or by oxygen alone. The first reaction involved the oxidation of p-methylphenylacetic acid with added benzyl alcohol. Product analysis by nmr indicated that the benzaldehyde: benzylalcohol ratio was 56:43 while the p-methylbenzaldehyde:p-methylbenzyl alcohol ratio was 151:18. With this large difference in ratios, it would appear that the two different aldehydes are generated by two different processes.

The second control experiment involved the reaction of p-methylbenzyl nitrate with cerium(III) and oxygen. When the product mixture was analyzed by nmr spectroscopy, p-methylbenzyl nitrate and p-methylbenzyl alcohol were identified as components of the mixture. No evidence for the formation of the p-methylbenzyldehyde could be found. Presumably, the formation of the p-methylbenzyl alcohol results from the hydrolysis of p-methylbenzyl nitrate.

A competitive oxidation of p-methylphenylacetic acid versus phenylacetic acid by CAN was carried out under an oxygen atmosphere. The results, (Table 5) indicate that the oxygen had no effect on the relative rates of oxidation of the two acids.

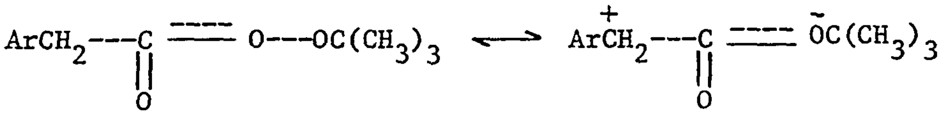
Mechanism of Oxidative Decarboxylation

The mechanism for the oxidative decarboxylation of substituted phenyl acetic acids by cerium(IV) involves initial complex formation in a rapid equilibrium step. Decomposition of the complex in which the α-carbon-carbon bond is broken to yield a substituted benzyl radical, carbon dioxide and cerium(III) is the rate determining step. The formation of the carboxylate radical is unlikely in view of the magnitude of the ρ value obtained in the competitive oxidations. The mechanism is presented in Scheme 2. The formation of the benzyl radical intermediate has been demonstrated by radical trapping experiments with oxygen to provide increased yields of aldehydic products.



Scheme 2. Proposed mechanism for the oxidative decarboxylation of substituted phenylacetic acids by cerium(IV)

The correlation of the relative rates of reaction by σ^+ values is thought to reflect carbenium ion character at the benzylic carbon in the activated complex. Bartlett and Ruchardt (66) have proposed that an activated complex similar to that indicated below adequately describes the decomposition of <u>tert</u>-butylperoxyphenylacetates.



$$\mathrm{ArCH_2}\text{---}\underset{\underset{\textstyle \mathrm{O}}{\|}}{\mathrm{C}}\;\overset{\text{----}}{\text{——}}\;\mathrm{O}\text{---}\mathrm{OC(CH_3)_3} \longleftrightarrow \mathrm{Ar}\overset{+}{\mathrm{C}}\mathrm{H_2}\text{---}\underset{\underset{\textstyle \mathrm{O}}{\|}}{\mathrm{C}}\;\overset{\text{----}}{\text{——}}\;\overset{-}{\mathrm{O}}\mathrm{C(CH_3)_3}$$

EXPERIMENTAL

Equipment

All nuclear magnetic resonance (nmr) spectra were measured on a Varian A-60A spectrometer. Chemical shifts are reported as δ-values in ppm from tetramethylsilane (TMS) as internal standard.

Materials

Commercial Chemicals

Table 8 lists the source of chemicals obtained commercially.

Table 8. Commercial chemicals

Compound	Source
Ceric ammonium nitrate (CAN)[a]	Baker
p-Methylphenylacetic acid[b]	Aldrich
m-Methylphenylacetic acid[b]	Aldrich
Phenylacetic acid	Eastman
p-Chlorophenylacetic acid[c]	Aldrich
m-Chlorophenylacetic acid	Aldrich

[a] Assumed equivalent weight of 548.

[b] Recrystallized from *n*-hexane.

[c] Recrystallized from carbon tetrachloride.

Prepared Compounds

p-Methylbenzyl nitrate   Procedure of Ferris and coworkers (77) was employed to provide 5.4 g of the nitrate: bp 70-2°/0.5 mm (lit (78) 60°/0.2 mm); nmr (CCl_4) δ 2.33 (s, 3H), 5.27 (s, 2H) and 7.15 (s, 5H).

Oxidations

Competitive Oxidations

All competitive oxidations were carried out under similar conditions. Because the analysis was performed by nmr, two different work-up procedures were employed. With the *p*-methylphenylacetic acid and *m*-methylphenylacetic acid a double extraction technique was employed. All percentages for the solvent systems used are volume percent.

General procedure A   To 2.00 mmoles of the appropriate phenylacetic acid in 35 ml of 50% aqueous acetonitrile was added a solution of CAN in the same solvent (amounts of CAN varied depending upon the substrates). The reaction mixture was heated on a steam bath with stirring until the reaction mixture had decolorized. The mixture was cooled, standard (*o*-toluic acid, 2.00 mmoles) was added and the mixture was poured into 25 ml of saturated sodium chloride solution. The mixture was extracted 3 times with 25-ml portions of ether and the combined ether extracts were washed 2 times with 10-ml portions of 1.2 N aqueous sodium hydroxide solution. The resulting alkaline solution was acidified with 5 ml of 6.0 N nitric acid and extracted 3 times with 10-ml portions of ether. These last ether extracts were combined and dried ($MgSO_4$). The ether was removed by rotary evaporation at reduced pressure and the residue was taken up in deuterochloroform and an nmr spectrum recorded.

General Procedure B   To 2.00 mmoles of the appropriate phenylacetic acid in 35 ml of 50% aqueous acetonitrile was added 15 ml of CAN in 15 ml of the same solvent. The reaction mixture was heated on a steam bath with stirring until the mixture had decolorized. The mixture was cooled, standard (bibenzyl, 1.00 mmole) was added and the mixture was poured into

25 ml of saturated aqueous sodium chloride solution. The mixture was extracted 3 times with 25 ml portions of ether and the combined ether extracts were washed 1 time with 25 ml of saturated aqueous sodium chloride solution and dried ($MgSO_4$). The ether was removed by rotary evaporation at reduced pressure and the residue was dissolved in deuterochloroform and a nmr spectrum was recorded.

Nmr analysis The spectra were all recorded on a 250 Hz scale with TMS as internal standard. With the double extraction technique, the peak areas of the methylene protons were multiplied by 1.5 and the peak area of the methyl protons of the p and m-methylphenylacetic acids was subtracted, yielding the peak area value for the phenylacetic acid. In the single extraction procedure, the ratio of the recovered starting materials was determined by expanding the signal for the methylene peaks on the 50 Hz scale and then using a cut and weigh procedure for determining the area. The results are presented in Table 9.

Radical Trapping Experiments

Reactions were performed under nitrogen and oxygen in a 100 ml 3-neck round bottom flask equipped with a sintered glass bubbler, reflux condenser and addition funnel with pressure equalizing side arm. The system was flushed with nitrogen or oxygen for 5 minutes prior to the start of the reaction and for nitrogen, a positive pressure was maintained throughout the reaction while the oxygen was bubbled through the mixture throughout the reaction. At this time, 4.00 mmoles of p-methylphenylacetic acid in 35 ml of 50% aqueous acetonitrile was added followed by 15 ml of a 50% aqueous acetonitrile solution of 8.00 mmoles of CAN. The reaction mixture was magnetically stirred at 25 ± 2° until the solution had decolorized.

Standard (mesitylene, 1.00 mmole) was added and the mixture was poured into 25 ml of saturated aqueous sodium chloride solution. The mixture was extracted 3 times with 25-ml portions of ether and the combined ether extracts were washed 3 times with 10-ml portions of 1.2 N aqueous sodium hydroxide solution and 3 times with 25-ml portions of saturated aqueous sodium chloride solution. The ether solution was dried ($MgSO_4$) and the solvent was removed by rotary evaporation at reduced pressure. The residue taken was dissolved in deuterochloroform and a nmr spectrum was recorded.

Table 9. Analysis of the competitive oxidations of substituted phenylacetic acids by CAN in 50% aqueous acetonitrile at 80°

Acids Competing		Peak Areas			mmoles	
A_1	A_2	A_1	A_2	Std.	A_1	A_2
p-CH_3	H	56.0	154.5	155.4	0.68	1.90
		64.3	167.2	168.7	0.72	1.90
		61.3	177.0	179.0	0.64	1.89
		57.6	96.6	92.8	1.18	1.95
m-CH_3	H	120.8	156.7	157.5	1.46	1.90
		118.5	152.8	154.3	1.46	1.89
		105.8	138.2	138.7	1.45	1.90
p-Cl	H	84.4	88.9	98.0	1.70	1.74
		89.1	94.6	147.9	1.17	1.21
		83.1	86.9	90.0	1.82	1.84
m-Cl	H	108.8	84.2	107.0	1.90	1.50
		102.4	76.6	101.5	1.89	1.44
		96.4	75.6	96.3	1.90	1.50
		111.9	84.4	111.0	1.89	1.45

Table 10. Radical trapping with oxygen in the CAN oxidation of p-methylphenylacetic acid at 25° in 50% aqueous acetonitrile

Atmosphere	Peak Area/H				mmoles			
	Std.	RCHO	ROH	$RONO_2$	Std.	RCHO	ROH	$RONO_2$
N_2	27.5	10.6	18.0	19.1	1.38	0.48	0.91	0.96
	18.5	9.0	12.4	17.2	1.27	0.62	0.85	1.18
O_2	51.8	79.7	11.7	9.2	1.25	1.92	0.28	0.22
	46.6	61.0	9.1	6.0	1.43	1.90	0.28	0.19

Competition Reaction in Oxygen Atmosphere

To 2.00 mmoles each of p-methylphenylacetic acid and phenylacetic acid in 35 ml of 50% aqueous acetonitrile, flushed for 5 minutes with oxygen, was added 4.00 g CAN in 15 ml of 50% aqueous acetonitrile. The reaction mixture was stirred mechanically at room temperature until the mixture had decolorized, during which time oxygen was bubbled through the reaction mixture. Standard (o-toluic acid, 2.00 mmoles) was added and the mixture was poured into 25 ml saturated aqueous sodium chloride solution and extracted 3 times with 25 ml ether. The combined ether layers were washed 2 times with 10 ml 1.2 N aqueous sodium hydroxide solution. The alkaline solution was acidified with 5 ml 6.0 N aqueous nitric acid and the resulting mixture was extracted 3 times with 10 ml ether. The ether solution was dried ($MgSO_4$) and the solvent was removed by rotary evaporation at reduced pressure, and the residue was dissolved in deuterochloroform for nmr analysis.

Table 11. Competitive oxidation of *p*-methylphenylacetic acid *versus* phenylacetic acid with CAN in an oxygen atmosphere at 25°

Acids competing		Peak Areas			mmoles	
A_1	A_2	A_1	A_2	Std.	A_1	A_2
p-CH_3	H	6.0	155.0	171.2	0.14	1.73
		26.3	166.7	176.2	0.28	1.81
		25.3	114.7	149.8	0.32	1.84

Carbon Dioxide Analysis

In a 100-ml 3-neck round-bottom flask was placed 4.00 mmoles of *p*-methylphenylacetic acid in 40 ml of 70% aqueous acetonitrile (0.35 N HNO_3). The flask was equipped with a sintered glass bubbler, a gas outlet tube attached to the absorption train, and an addition funnel. Nitrogen, the carrier gas, was bubbled through the solution for 5 minutes and through the attached U-tube filled with anhydrous calcium chloride. At this time, the rest of the carbon dioxide absorption train (U-tube filled with Ascarite and U-tube filled with anhydrous calcium chloride and a gas bubbler) was attached and nitrogen was bubbled through the solution for 5 minutes more. A solution of 8.8 mmoles of CAN in 10 ml of 70% aqueous acetonitrile (0.35 N HNO_3), which had previously been degassed with nitrogen, was added and the reaction mixture was heated at 55° with nitrogen bubbling until the mixture had decolorized. The nitrogen bubbling was continued for another 5 minutes, the absorption train broken, and the U-tube containing the Ascarite immediately weighed. The amount of carbon dioxide adsorbed was determined by the weight difference of the Ascarite U-tube immediately before and immediately after the reaction was performed.

Table 12. Carbon dioxide analysis for the p-methylphenylacetic acid oxidation by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 55°

mmoles acid	mmoles CAN	weight of Ascarite before run (g)	weight of Ascarite after run (g)	g CO_2 absorbed
4.00	8.8	86.3043	86.4440	0.1397
4.00	8.8	86.4481	86.5913	0.1432
4.00	8.8	89.4110	89.5477	0.1367

Control Reaction with Added Benzyl Alcohol

To 4.00 mmole of p-methylphenylacetic acid and 1.00 mmole of benzyl alcohol in 40 ml of 50% aqueous acetonitrile was added 8.00 mmoles of CAN in 10 ml of 50% aqueous acetonitrile. The reaction was run at room temperature with oxygen bubbling through the reaction mixture until the solution had decolorized. Standard was added and the mixture was poured into 25 ml saturated aqueous sodium chloride solution and extracted 3 times with 25 ml ether. The combined ether extracts were washed 1 time with 25 ml saturated aqueous sodium chloride solution, dried ($MgSO_4$), the solvent evaporated and the residue dissolved in deuterochloroform for nmr analysis.

Control Reaction with p-Methylbenzyl Nitrate

To 50 ml of a 50% aqueous acetonitrile solution of cerium(III) (prepared by reducing CAN with pinacol) was added 0.95 mmoles of p-methylbenzyl nitrate. Oxygen was bubbled through the reaction mixture for the same length of time as the decarboxylation at room temperature. The mixture was worked up as previously described to yield p-methylbenzyl nitrate (0.58 mmole) and p-methylbenzyl alcohol (0.30 mmole).

PART II

REACTIONS OF CERIC AMMONIUM NITRATE WITH 2,5-DISUBSTITUTED FURANS

SUMMARY OF PART II

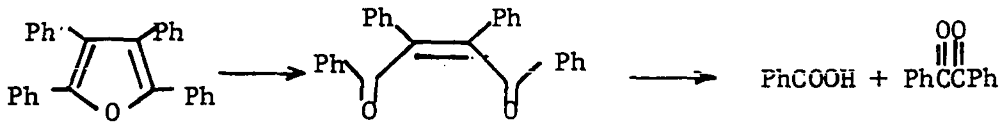
The oxidation of 2,5-diarylfurans and 2-aryl-5-alkylfurans has been found to generate good to excellent yields of cis-1,4-diaryl-2-butene-1,4-diones and cis-1-aryl-4-alkyl-2-butene-1,4-diones. If the reaction is performed in methanol as solvent, the major product generated is 2-methoxy-1,4-diarylbutane-1,4-dione when 2,5-diphenylfuran is used as substrate and 3-methoxy-1-phenylpentane-1,4-dione when 2-phenyl-5-methylfuran is used as substrate.

The oxidation of 2,5-dimethylfuran in methanol by ceric ammonium nitrate generates 2-methoxymethyl-5-methylfuran in good yield. The addition of cyanide anion or methoxide anion in the reaction mixture produces two additional products, cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran.

A mechanism for the oxidation of 2,5-disubstituted furans by ceric ammonium nitrate has been proposed. The mechanism involves initial radical cation formation by electron transfer from the furan nucleus as the rate determining step. The processes which follow radical cation formation are dependent upon the substrate and the solvent.

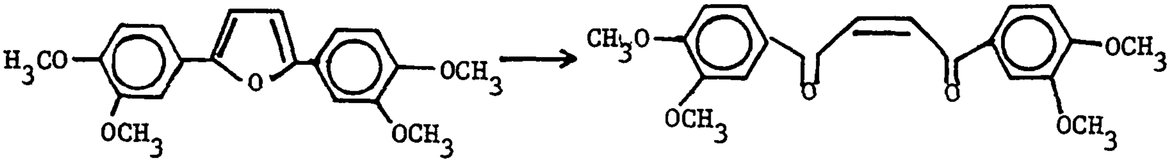
HISTORICAL

One of the first reported oxidations of a furan was carried out in 1871 by von Richter (79); tetraphenylfuran was oxidized with chromic acid to yield the corresponding cis-dibenzoylstilbene, which upon being further



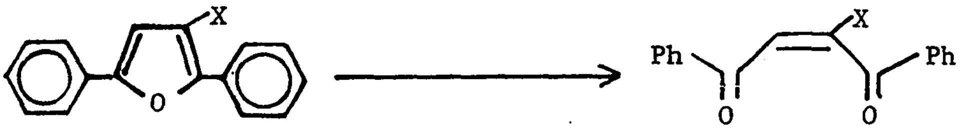
heated, yielded benzoic acid and benzil.

Later, Kawai and coworkers (80) oxidized 2,5-dimethylfuran to cis-3-hexene-2,4-dione by dropwise addition of a chromic acid solution at 0°. In 1965, Traverso and Pollini (81) oxidized 2,5-diveratrylfuran with potassium dichromate in acetic acid. An addition compound was formed



which spontaneously decomposed to cis-diveratroylethylene.

Von Richter (79) and Zinnin (82) also oxidized tetraphenylfuran to cis-dibenzoylstilbene with nitric acid. Bailey and coworkers (83, 84, 85) have oxidized a series of 3-substituted-2,5-diphenylfurans with nitric acid at -15° to 0° with yields ranging from 62% to 81%. The oxidation

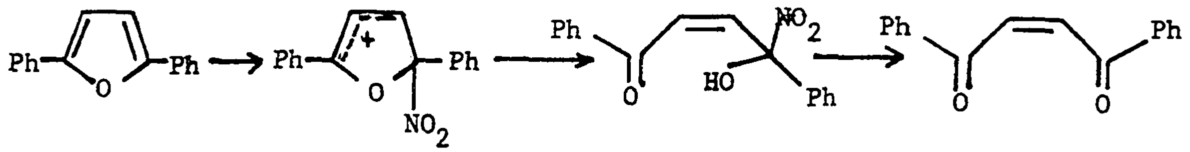


	Yield
X = Br	62%
= $CH(CH_3)_2$	81%
= OCH_3	78%
= $CH_2CH_2CH_3$	77%
= CH_2Ph	65%

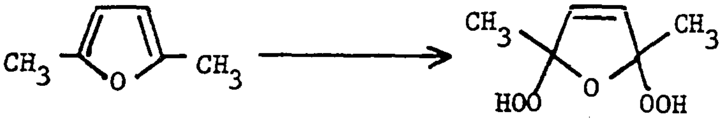
of 3,4-dimethyl-2,5-diphenylfuran (83) with nitric acid at -10° furnished a 94% yield of cis-2,3-dibenzoyl-2-butene.

Lutz and Wilder (86) studied the reaction of nitric acid with 2,5-diarylfurans and proposed that the reaction proceeds through 1,4 addition of nitric acid to the furan nucleus, followed by loss of nitrous acid to yield the cis-diaroylethylene. Later, Lutz and Kibler (87) used 2,5-dimesitylfuran as substrate for nitric acid oxidation and found that the furan was inert, which was interpreted as being consistent with the 1,4 addition mechanism.

Lutz and Boyer (88) have oxidized a series of furans with a mesityl group at the 2 position and found that nitric acid oxidized the furans smoothly to the expected cis-enediones. Since these results are not consistent with the previously proposed 1,4 addition mechanism, a new mechanism was postulated.

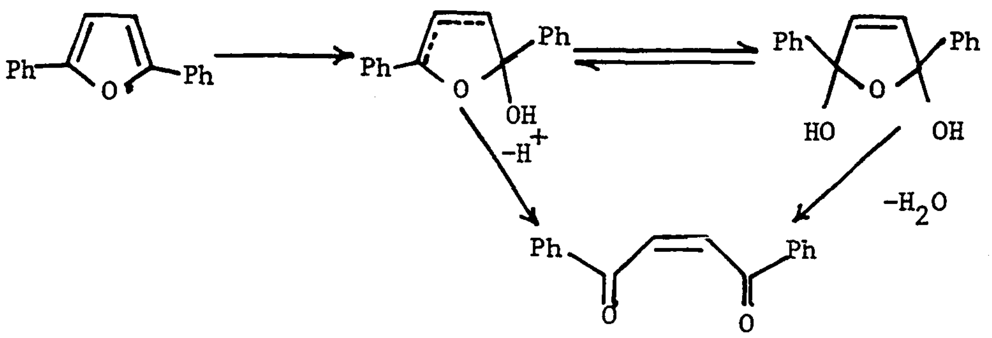


Hydrogen peroxide has been used as an oxidant for furans by Lapkova and coworkers (89, 90). It was found that the oxidation of furan yielded maleic acid as the major product. The rate of the oxidation and the yield of maleic acid were increased by the presence of hydrochloric acid, the use of dioxane as solvent or the presence of Fenton's Reagent in acetic acid. Seebach (91) isolated a 2,5-bishydroperoxide from the oxidation of



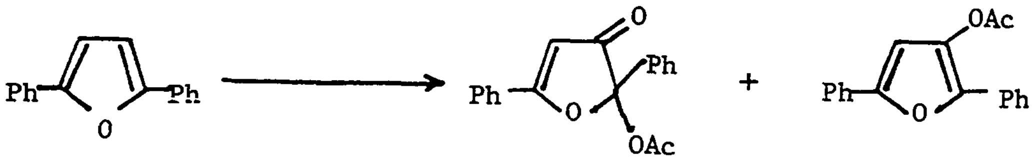
2,5-dimethylfuran with hydrogen peroxide.

Lutz and Dien (92) studied the hydrogen peroxide oxidation of a series of 2,5-diarylfurans. Unlike the nitric acid oxidations, 2,5-dimesitylfuran was oxidized by hydrogen peroxide to cis-dimesitoylethylene. A mechanism similar to the proposed mechanism for the nitric acid oxidations was postulated. The mechanism involves electrophilic attack by hydrogen peroxide to give the two intermediates shown below, which decompose to yield the observed products.

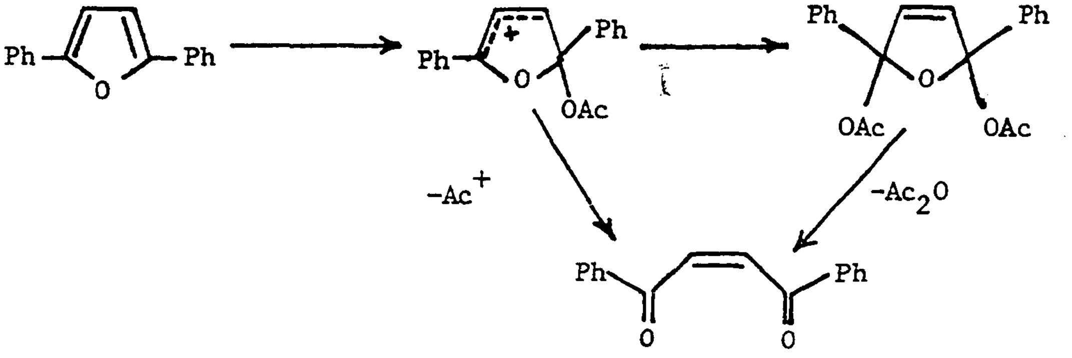


The lead(IV) carboxylate oxidation of furan has been examined by Elming and Clauson-Kaas (93). In these oxidations both the cis and trans-2,5-dicarboxy-2,5-dihydrofurans were generated where R = isopropyl, phenyl and n-propyl. Elming (94) reported that the lead tetraacetate (LTA) oxidation of 3-isopropylfuran yields 2,5-diacetoxy-3-isopropyl-2,5-dihydrofuran which is hydrolyzed to isopropylmalealdehyde. Clauson-Kaas (95) has oxidized furan to 2,5-diacetoxy-2,5-dihydrofuran with LTA.

Dien and Lutz (96) oxidized a series of 2,5-diarylfurans with LTA in chloroform and in acetic acid. In chloroform, the oxidation yielded the cis-1,4-diaroylethylene but as in the case of nitric acid oxidation, 2,5-dimesitylfuran was inert. In the oxidations performed using acetic acid as solvent, the products isolated are 3-acetoxy-2,5-diarylfuran and



2-acetoxy-2,5-diarylfuran-3-one. A mechanism is postulated for the oxidation in chloroform which is similar to the mechanism for the nitric



acid oxidation, since it involves electrophilic attach by $^{+}OOCCH_3$ or a $Pb(OOCCH_3)_x^{+}$ species on the furan to form an intermediate which decomposes to the observed products.

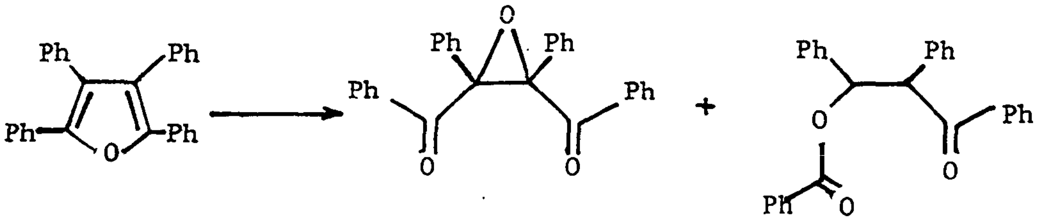
The ozonolysis of furans has been studied by a number of workers. Jibben and Wilbaut (97) reported that furan derivatives react with ozone to form a diozonide in approximately 60% yield. The remaining furan reacts with ozone to form a monoozonide. Products are derived from both adducts.

Bailey and Colomb (98) have studied the ozonolysis of 2,5-diphenylfuran and found that cis-1,2-dibenzoylethylene is generated in 12% yield after the absorption of one molar equivalent of ozone. The reaction is thought to proceed through the 1,4 addition of ozone to the furan nucleus.

Later, White et al. (99, 100) studied the ozonolysis of a series of diarylfurans; from a product study, a mechanism was postulated which involves two types of ozone addition. The first is an electrophilic attack at a reactive α position, similar to that postulated by Lutz and coworkers (92, 101), to generate a σ complex. The second mode of attack occurs at the 2,3 bond either through a four center complex or through a π complex. The proposed mechanisms can account for the products obtained from the ozonolysis of 2,5-diphenylfuran, 3,4-diphenylfuran, 2,5-dianisylfuran and 2,5-dimesitylfuran.

The photooxidation of furans has been studied by a number of workers. Martel (102) irridated 2,5-diphenylfuran and 2,3,4,5-tetraphenylfuran in carbon disulfide to generate photooxides which were too unstable to isolate. Reduction of these photooxides gave cis-dibenzoylethylene and cis-dibenzoylstilbene.

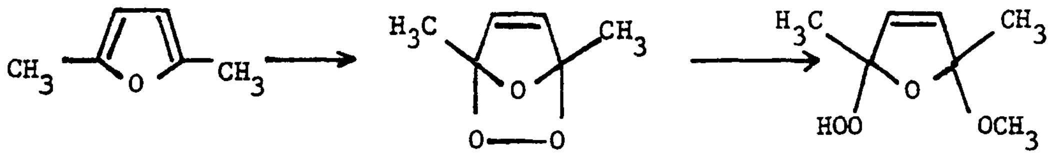
Wasserman and Liberles (103) photooxidized 2,3,4,5-tetraphenylfuran in methanol and acetone. In methanol the products isolated were cis-dibenzoylethylene and 2,5-dimethoxy-2,3,4,5-tetraphenyl-2,5-dihydrofuran while the photooxidation of 2,3,4,5-tetraphenylfuran in acetone yielded



cis-dibenzoylstilbene oxide and α-benzoyl-α'-benzoyloxy-cis-stilbene.

The photooxidation of 2-methylfuran by Holecek and Horak (104) gave α-acetylacrylic acid while van der Merwe and Garbers (105) have photochemically oxidized 3-methylfuran to 4-ethoxy-2-methylbut-3-enolide.

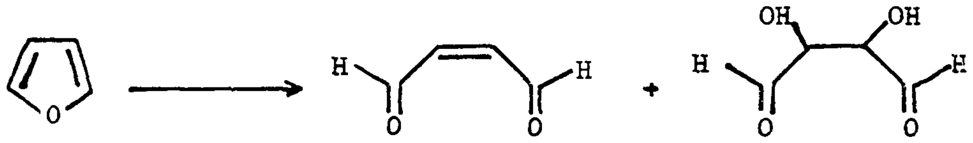
The photooxygenation of 2,5-dimethylfuran (106) in methanol was found to furnish high yields of 2-methoxy-5-hydroperoxy-2,5-dimethyl-2,5-dihydrofuran. It was postulated that the reaction proceeds *via* solvolytic ring opening of an initially formed *endo* peroxide.



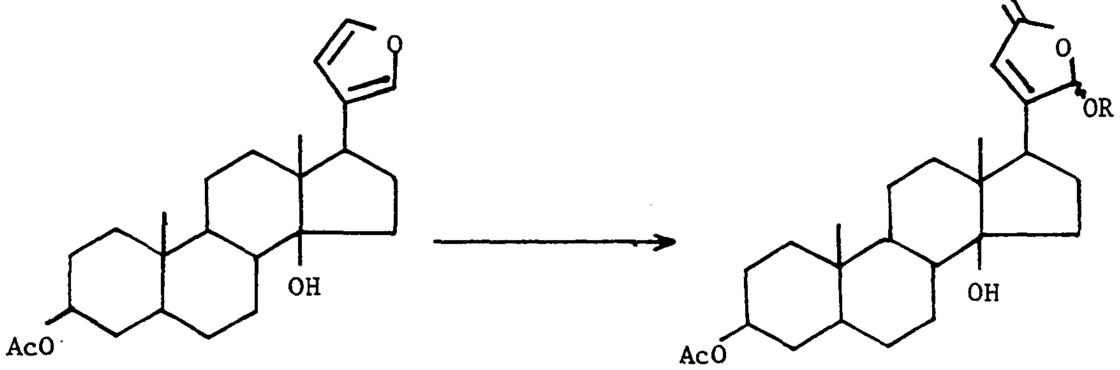
The oxidation of 2,5-dimethylfuran with singlet oxygen formed *in situ* by the reaction of sodium hypochlorite and hydrogen peroxide has been studied by Foote and Wexler (107). It was found that 2,5-dimethyl-2-hydroperoxy-2,5-dihydrofuran is generated in 84% yield. This is the same product that is produced to 74% by the photosensitized autoxidation of 2,5-dimethylfuran in methanol.

The oxidation of 2,3,4,5-tetraphenylfuran by phosphorus pentachloride to *cis*-dibenzoylstilbene in excellent yield has been reported by Lutz and Welstead (108).

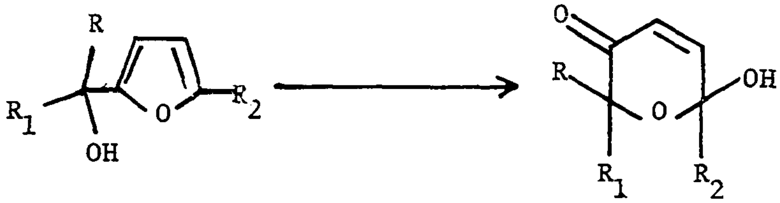
The hydroxylation of furan with osmium tetroxide was carried out by Clauson-Kaas and Fakstorp (109). The products, isolated as the phenylhydrazones, were *meso*-tartaraldehyde and malealdehyde.



The reaction of furans with peracids has also been studied. Catala and Defaye (110) oxidized furan with p-nitroperbenzoic acid and isolated 2-oxo-5-hydroxy-2,5-dihydrofuran. Later Ferland and coworkers (111) oxidized 17 -[2-furyl] -5β, 14β-androstan-3β, 14β-diol-3-acetate with peracetic acid to give a 16% yield of 3β-14β-21-trihydroxy-23-oxo-5β-cara-20(24)enolide-3-acetate.



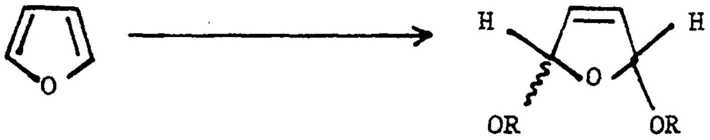
Recently, Lefebvre (112) oxidized a series of 2-furanmethanols with peracetic or m-chloroperbenzoic acid to 6-hydroxy-2H-pyran-3(6H)ones.



The reaction of 17-2-furyl-3-methoxy-1,3,5(10)-estratrien-17-ol was converted in 65% yield to 17,24-epoxy-24-hydroxy-19,21-dinorchola-1,3,5-(10),22-tetraen-20-one in which the pyran system is attached at the 17 position in a spiro manner.

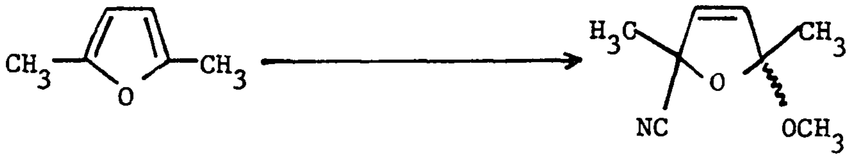
Earlier, Elming (113) oxidized 3-isopropylfuran with peracetic acid in chloroform to give a 50% yield of 2-hydroxy-3-isopropyl-5-oxo-2,5-dihydrofuran, while the same reaction in dioxane-water solvent gave 2-oxo-3-isopropyl-2,5-dihydrofuran in 60% yield.

The electrolytic oxidation of furans has been studied by a number of workers. Clauson-Kaas and coworkers (114, 115) have studied the electrolytic methoxylation and ethoxylation of furan to generate



2,5-dialkoxy-2,5-dihydrofuran in 73% and 63% yields. Elming (116) has methoxylated 3-isopropylfuran electrolytically to 2,5-dimethoxy-3-isopropyl-2,5-dihydrofuran. Baggaley and Brettle (117, 118) have electrolyzed a series of furans in sodium acetate-acetic acid solution or in sodium methoxide-methanol solution. In the case of the electrolysis of 2,5-dimethylfuran in the sodium acetate-acetic acid solution the product was 2,5-bis(acetoxymethyl)furan while the electrolysis of 2,5-dimethylfuran in sodium methoxide methanol solution gave a mixture with cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran as the major products. The authors feel that the products arise from anodic oxidation of the furan ring and subsequent nucleophilic attack on cationic intermediates. Ross and coworkers (119) have electrochemically oxidized 2,5-dimethylfuran to 2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran. These authors also feel that the furan ring is initially oxidized to the radical cation.

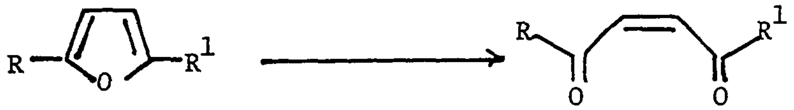
More recently, Yoshida and coworkers (120, 121) have electrolyzed a methanolic sodium cyanide solution of 2,5-dimethylfuran to a mixture of cis and trans-2-cyano-5-methoxy-2,5-dimethyl-2,5-dihydrofuran. Again,



the proposed mechanism for the oxidation involves initial oxidation of the furan followed by nucleophilic attack on a cationic intermediate.

RESULTS

A series of 2,5-disubstituted furans was oxidized with ceric ammonium nitrate (CAN) at 25° in a variety of solvents. The reaction times for the oxidation varied from 5 seconds to 30 minutes, depending upon the solvent and the substrate. In the case of 2-aryl-5-alkylfurans or 2,5-diarylfurans, the major product isolated was the *cis*-1- aryl-4-alkyl-2-butene-1,4-dione and *cis*-1,4-diaryl-2-butene-1,4-dione, respectively, in good to excellent yield.



In Table 13 are presented the results of the oxidation of 2,5-diphenylfuran in a number of solvents with two equivalents of CAN.

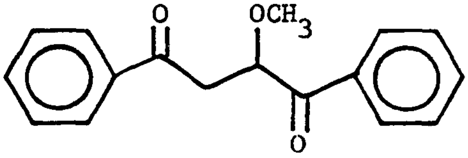
Table 13. Yields of *cis*-1,2-dibenzoylethylene from the oxidation of 2,5-diphenylfuran with CAN at 25°

Solvent	Furan (mmoles)	Reaction Time (minutes)	Yield[a] (mmoles)	Yield %
CH_3CN	2.00	30	1.86 ± 0.03[b]	93.0 ± 1.5
AcOH	2.0	30	1.81 ± 0.2	90.5 ± 1.0
CH_3OH	2.0	1	1.88 ± 0.03	94.0 ± 1.5
tert-BuOH	2.00	30	1.90 ± 0.01	95.0 ± 1.0

[a] Yields determined on unpurified product using hexadecane as standard.

[b] Standard deviations are based on at least 3 runs.

When methanol was used as solvent, a second product was isolated in good yield if the reaction time was extended. The product has tentatively been identified a 2-methoxy-1,4-diphenyl-butene-1,4-dione using spectral methods.



The oxidation of a series of 2,5-diarylfurans was carried out in acetonitrile and the products were isolated and purified by recrystallization. The isolated yield of cis-1,4-diphenyl-2-butene-1,4-dione was determined for the oxidation of 2,5-diphenylfuran in a series of solvents.

Table 14. Isolated yields of cis-1,4-diaryl-2-butene-1,4-diones from the oxidation of 2,5-diarylfurans in 95% aqueous acetonitrile with CAN at 25°

Furan (mmoles)	Weight of isolated enedione (mg)	Yield %
2,5-diphenyl (2.00)	436.3	92
2-p-tolyl-5-phenyl (2.00)	460.3	91
2,5-di-p-tolyl (1.00)	245.3	88

Table 15. Isolated yield of 1,4-diphenyl-2-butene-1,4-dione from the oxidation of 2,5-diphenylfuran with CAN in various solvents at 25°

Solvent	Weight of isolated product (mg)	Yield[a] %
95% aqueous acetonitrile	436.5	92
acetonitrile	438.0	94
90% aqueous acetic acid	384.3	83
95% aqueous acetic acid	416.4	88
acetic acid	394.1	87
methanol	426.3	90

[a] Yields are based on 2.00 mmoles of 2,5-diphenylfuran.

It was found that for the oxidation of 2,5-diphenylfuran in acetonitrile, there is a secondary oxidation which probably does not involve cerium. It was also found that the addition of 5% water to the reaction mixture suppresses the secondary oxidation. The addition of another 10% water to the reaction mixture does not seem to further inhibit the secondary oxidation. In order to determine the stoichiometry of the CAN oxidation of 2,5-diarylfurans, a series of oxidations in 95% and 85% aqueous acetonitrile were performed with insufficient CAN to oxidize all the furan and the ratio of product to furan was determined from an nmr analysis of the product mixture. The results presented below indicate that the oxidation of 2,5-diarylfurans requires 2 equivalents of CAN to convert 1 equivalent of furan to product.

Table 16. Oxidation of 2,5-diphenylfuran to 1,4-diphenyl-2-butene-1,4-dione with insufficient CAN to determine the stoichiometry of the reaction in aqueous acetonitrile at 25°

% water added	equivalents CAN / equivalent furan	Reaction time (minutes)	Ratio Pdt./furan
0	0.55	2	82:18
5	0.55	2	27:73
5	1.1	2	56:44
5	1.1	0.25	56:44
15	1.1	0.25	55:45

The competitive oxidation of a series of 2,5-diarylfurans with CAN was carried out using 95% aqueous acetonitrile as solvent. The reactions were run with 0.4 mmoles of each furan in solution to which 1.00 mmoles of CAN was added with stirring. The reaction was quenched by flooding with water. The resulting aqueous mixture was extracted with benzene, and the extract was analyzed by glpc.

Table 17. Relative rates of oxidation of 2,5-diarylfurans by CAN in 95% aqueous acetonitrile at 25°

Furan	k_X/k_H	$\log (k_X/k_H)$
2,5-di-*p*-tolyl	5.03 ± 0.09	0.702
2-*p*-tolyl-5-phenyl	2.32 ± 0.04	0.365
2-*p*-chlorophenyl-5-phenyl	1.60 ± 0.04	0.204
2,5-diphenyl	1.00	0.000
2,5-di-*p*-chlorophenyl	0.407 ± 0.003	-0.390

Figure 2. Hammett plot ($\sigma^+ + \sigma^+$) for the CAN oxidation of 2,5-diarylfurans in 95% aqueous acetonitrile at 25°

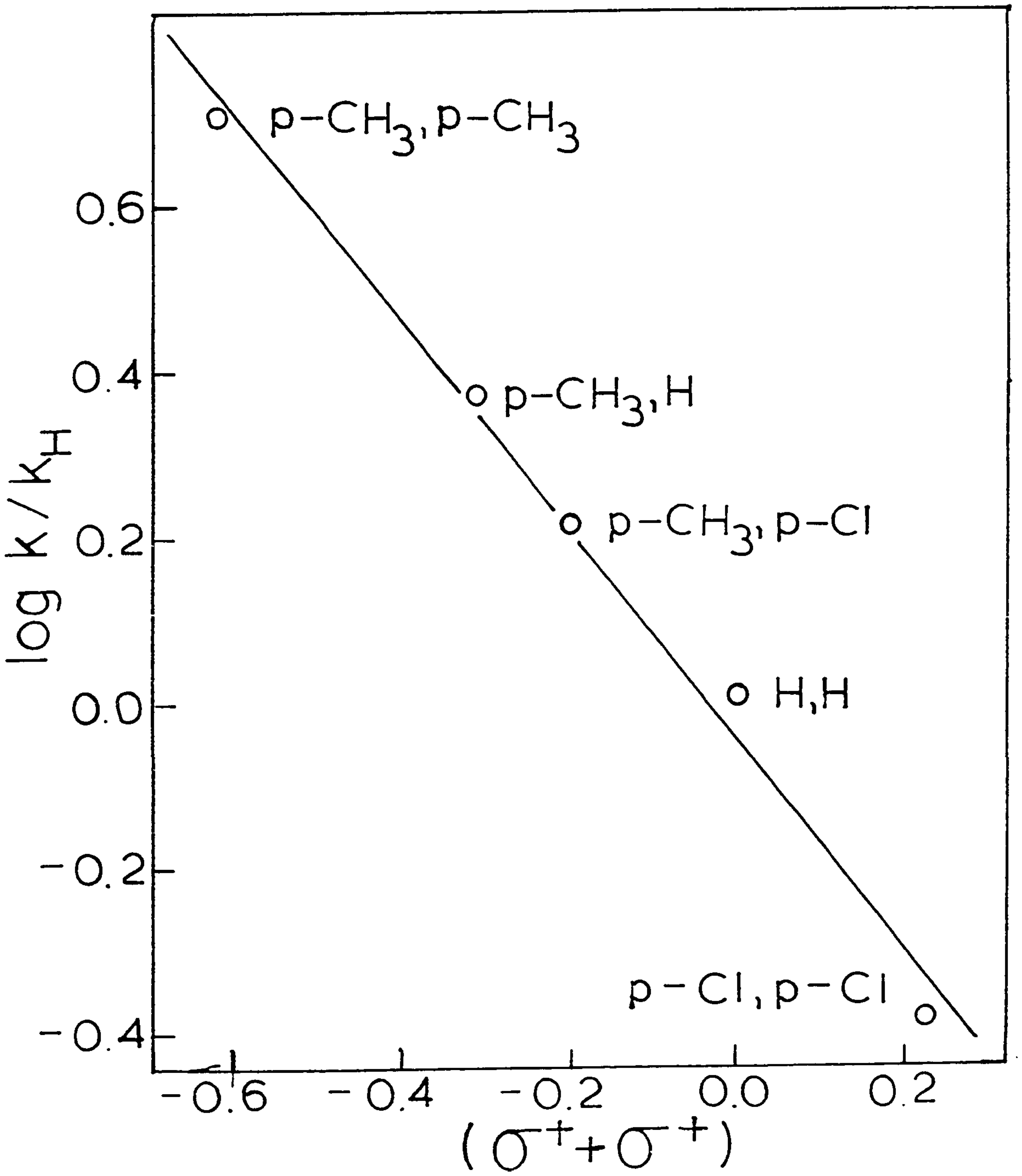
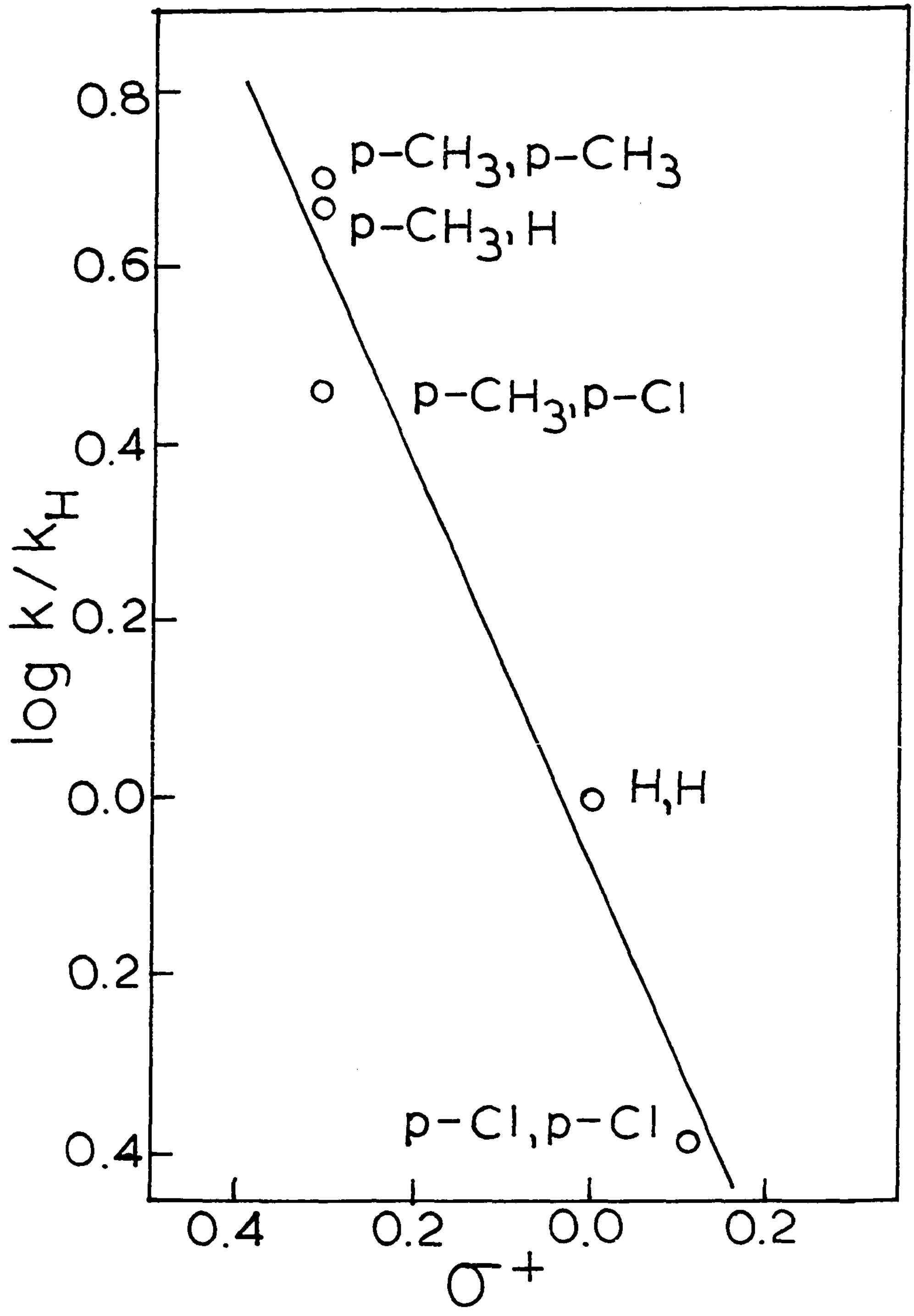

p-CH3, p-CH3
p-CH3, H
p-CH3, p-Cl
H, H
p-Cl, p-Cl
0.6
0.4
0.2
0.0
-0.2
-0.4
log k / kH
-0.6
-0.4
-0.2
0.0
0.2
(σ+ + σ+)

Figure 3. Hammett plot (σ^+) for the CAN oxidation of 2,5-diarylfurans in 95% aqueous acetonitrile at 25°


log k/k$_H$
0.8
0.6
0.4
0.2
0.0
0.2
0.4
0.4
0.2
0.0
0.2
σ$^+$
p-CH$_3$, p-CH$_3$
p-CH$_3$, H
p-CH$_3$, p-Cl
H, H
p-Cl, p-Cl

The log (k_X/k_H) values were then plotted against $(\sigma^+ + \sigma^+)$ (Table 18) and σ^+ (Table 19). These plots appear in Figure 2 and Figure 3.

Table 18. $(\sigma^+ + \sigma^+)$ values

Substituents	$(\sigma^+ + \sigma^+)$[a]
p-CH_3,p-CH_3	-0.622
p-CH_3,H	-0.311
p-CH_3,p-Cl	-0.197
H,H	0.000
p-Cl,p-Cl	0.228

[a] Values obtained from reference (57).

The oxidation of 2-phenyl-5-methylfuran was also carried out in a series of solvents to give good yields of 1-phenyl-2-pentene-1,4-dione. The results of these oxidations are given in Table 19.

Table 19. Yields of cis-1-phenyl-2-pentene-1,4-dione from the oxidation of 2-phenyl-5-methylfuran with 2 equivalents of CAN in various solvents at 25°

Solvent	Reaction time (sec)	Yield[a,b] (mmoles)	Yield %
CH_3OH	15	0.82 ± 0.04[c]	41 ± 2
CH_3CN	30	1.50 ± 0.07	75 ± 3
AcOH	1800	mixture of cis and trans	

[a] Yields based on unpurified product by nmr analysis using benzyl ether as standard

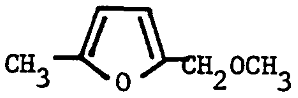
[b] Yields based on 2.00 mmoles of 2-phenyl-5-methylfuran.

[c] Standard deviations based on at least 3 runs.

When the oxidation of 2-phenyl-5-methylfuran by CAN in acetonitrile was carried out on 10 mmoles of furan, the product mixture isolated after 30 seconds at room temperature consisted of 6.6 mmoles of *cis*-1-phenyl-2-pentene-1,4-dione and 1.0 mmole of *trans*-1-phenyl-2-pentene-1,4-dione. Attempts to separate the mixture by glpc or column chromotography induced isomerization of the *cis*-1-phenyl-2-pentene-1,4-dione to the *trans*-1-phenyl-2-pentene-1,4-dione. Separation was finally achieved by thick layer chromatography, however, some isomerization was also noted.

If the oxidation of 2-phenyl-5-methylfuran is run with methanol as solvent, a second product can be isolated in 20 ± 3% after 15 seconds of reaction. If the reaction time is extended, this material is the only product isolated from the oxidation. The product has been identified as 3-methoxy-1-phenylpentane-1,4-dione by spectral methods.

The oxidation of 2,5-dimethylfuran was also studied in a variety of solvents. The product from the reaction performed in methanol was identified and in this oxidation, the product generated was not the expected *cis*-3-hexene-2,4-dione but 2-methoxymethyl-5-methylfuran. In



the oxidation of 2,5-dimethylfuran in acetonitrile and acetic acid generated complex mixtures and/or polymers.

Table 20. Yield of 2-methoxymethyl-5-methylfuran from the oxidation of 2,5-dimethylfuran with CAN in methanol at 25°

mmoles furan	Reaction time (minutes)	Yield[a] (mmoles)	Yield %
4.00	30	2.53 ± 0.17	63.2 ± 4

[a] Standard deviation is based on 3 runs.

If the oxidation of 2,5-dimethylfuran by CAN in methanol is carried out with added methoxide anion or added cyanide anion, two new products, cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran are generated in a 50:50 mixture. The addition of chloride anion or nitrate anion had no effect on the initial reaction; only 2-methoxymethyl-5-methylfuran could be detected in the product mixture.

Table 21. Oxidation of 2,5-dimethylfuran by CAN in methanol at 25° with added anions

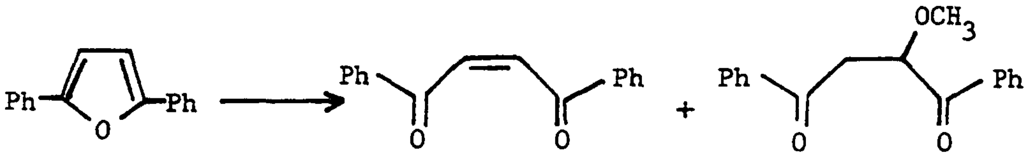
Salt added	$\frac{\text{equivalents salt}}{\text{equivalent furan}}$	Reaction time (minutes)	Relative yield[a]	
LiCl	10	50	trace	100
NH_4NO_3	15	30	0	100
$NaOCH_3$	1	30	20	80
$NaOCH_3$	10	30	82	18
KCN	2	30	43	57
NaCN	2	30	44	56
NaCN	6	30	77	23
NaCN	10	30	88	12

[a] Yields based on nmr analysis of reaction mixture.

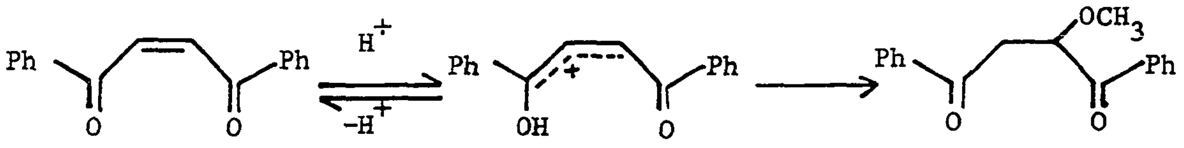
DISCUSSION

Product Studies

The oxidation of 2,5-diphenylfuran with ceric ammonium nitrate gave excellent yields of cis-1,4-diphenyl-2-butene-1,4-dione. Solvent changes had little effect upon yields or products, however, from oxidation in methanol, a second product was isolated which may be accounted for by



the addition of methanol across the double bond of the cis-1,4-diphenyl-2-butene-1,4-dione. The yield of 2-methoxy-1,4-diphenyl-butane-1,4-dione ranged from 5% after 5 seconds to 90% after 30 minutes. A reasonable pathway for the addition of the methanol involves protonation of one of



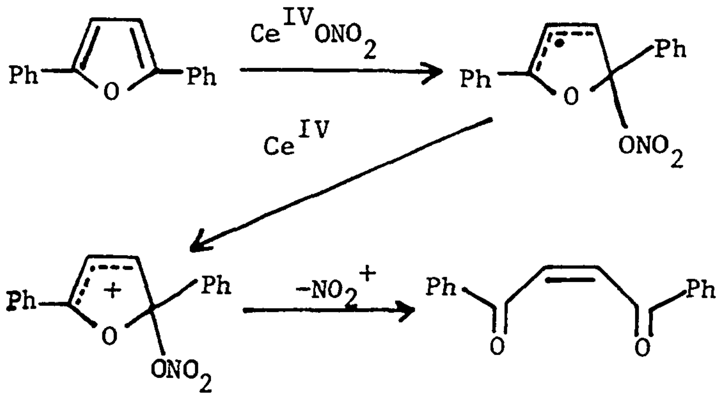
the carbonyl groups followed by nucleophilic attack by methanol to generate the observed product.

The oxidation of 2-phenyl-5-methylfuran also produced a ring opened product, 1-phenyl-2-pentene-1,4-dione in good yield. The oxidation of the furan in methanol with CAN in methanol also yielded a second product which has been identified as 3-methoxy-1-phenylpentane-1,4-dione. The assignment of the methoxy substituent arises from a comparison of the nmr spectrum of this product with the nmr spectrum of the product obtained from the oxidation of 2,5-diphenylfuran in methanol. The spectrum of 2-methoxy-1,4-diphenylbutane-1,4-dione includes a triplet due to the methine proton α to the methoxy group at δ 5.20, while the spectrum of the product from the oxidation of 2-phenyl-5-methylfuran contains a triplet at δ4.13 (the absorption due to the corresponding proton in this product).

The oxidation of 2,5-dimethylfuran provided identifiable products only when methanol was employed as solvent. In acetonitrile as solvent, the products appeared to be polymeric in nature while the oxidation in acetic acid produced numerous products. The CAN oxidation, in methanol, of 2,5-dimethylfuran provided a good yield of 2-methoxymethyl-5-methylfuran. The addition of sodium or potassium cyanide or sodium methoxide to the reaction mixture led to the production of a new product mixture consisting of both 2-methoxymethyl-5-methylfuran and cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran. The addition of lithium chloride or ammonium nitrate did not alter the course of the initial reaction, generation of 2-methoxymethyl-5-methylfuran.

Mechanistic Studies

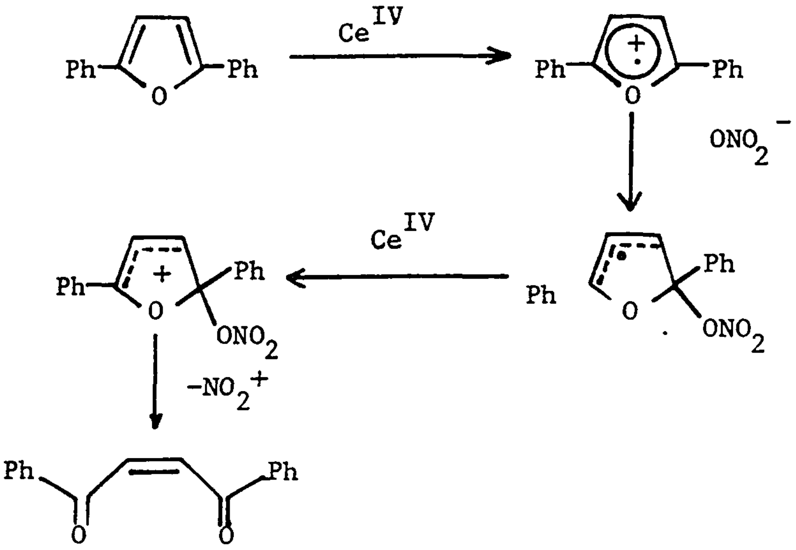
In other oxidations of 2,5-diarylfurans by different oxidants, the general mechanism postulated involved the addition of an electrophile to the 2-position of the furan or a 1,4-addition across the 2,5-positions (88, 92, 96, 106). A mechanism similar to these has been postulated for the cerium(IV) oxidation of 1,3,5-cycloheptatriene by Trahanovsky, Young, and Robbins (122). Muller and coworkers (123) have also postulated a similar mechanism for the oxidation of olefins by cerium(IV). The oxidation of 2,5-diphenylfuran could proceed through an "addition-in" mechanism analogous to those previously postulated as presented in Scheme 3 below.



Scheme 3. Proposed radical addition for the CAN oxidation of 2,5-diphenylfuran

Recently, the anodic oxidation of 2,5-dimethylfuran has been carried out in a number of different solvents. The proposed mechanism for these oxidations involves initial formation of a radical cation intermediate followed by further reaction leading to products (117, 118, 119, 120, 121). The generation of radical cations in the oxidation of aromatic systems by metal ions has been postulated by a number of workers (124, 125, 126). Again, a similar mechanism can be postulated for the cerium(IV) oxidation of 2,5-diphenylfuran.

In order to differentiate between the two mechanistic possibilities, a Hammett $\rho\sigma$ correlation was performed using 2,5-diarylfurans as substrates. If the radical addition pathway was operative and radical "addition-in" was rate determining, a correlation with either σ or σ^+ would be expected



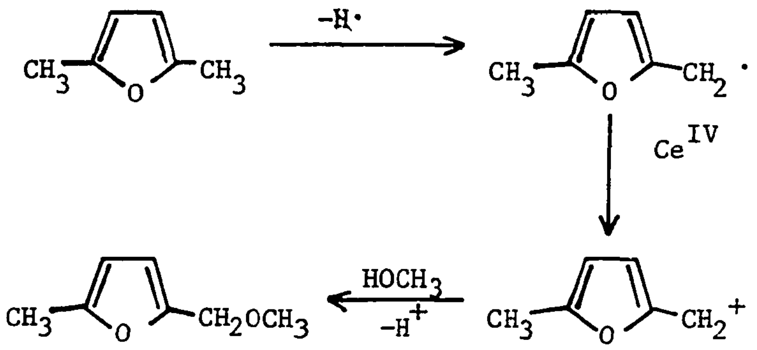
Scheme 4. Proposed radical cation mechanism for the oxidation of 2,5-diphenylfuran by CAN

since only one of the aryl groups could participate in stabilization of the generated radical intermediate. In addition, one would expect no difference in the relative rates of oxidation for the oxidation of a series of furans including: 2,5-di-p-tolylfuran, 2-p-tolyl-5-phenylfuran and 2-p-tolyl-5-p-chlorophenyl furan since radical addition should occur so as to generate the more stable radical, in this case the "p-methylbenzyl" radical. If, however, the reaction proceeds through a radical cation pathway and radical cation formation is the rate determing step; both aryl groups should participate in stabilization or destabilization of the intermediate radical cation. In this case, one would expect a

Hammett correlation with either ($\sigma^+ + \sigma^+$) or ($\sigma + \sigma$). For the radical cation mechanism, the relative rates for the series of furans: 2,5-di-p-tolylfuran, 2-p-tolyl-5-phenylfuran and 2-p-tolyl-5-p-chlorophenylfuran would be expected to be different. When the correlation was performed, it was found that the best correlation was obtained with ($\sigma^+ + \sigma^+$) generating a ρ value of -1.27 ± 0.07 while the correlation with σ^+ generated a ρ value of -2.24 ± 0.29. As can be seen in Table 18 , the relative rate values for the three designated furans are different, as would be expected if the reaction proceeded through a radical cation intermediate and formation of the radical cation was rate determining.

In the oxidation of 2,5-dimethylfuran employing methanol as solvent, the product obtained is not the ring opened diketone, but a side chain methoxylated product, 2-methoxymethyl-5-methylfuran. It is possible that this product could arise by a radical process involving α-hydrogen atom abstraction by a methoxide radical or a cerium species to generate a radical intermediate which is further oxidized to the cation by cerium(IV) followed by nucleophilic attack by methanol to generate the observed products. This mechanism is unlikely since the oxidation of alcohols by CAN do not generate alkoxy radicals (127) and CAN does not abstract even very reactive hydrogen atoms (123).

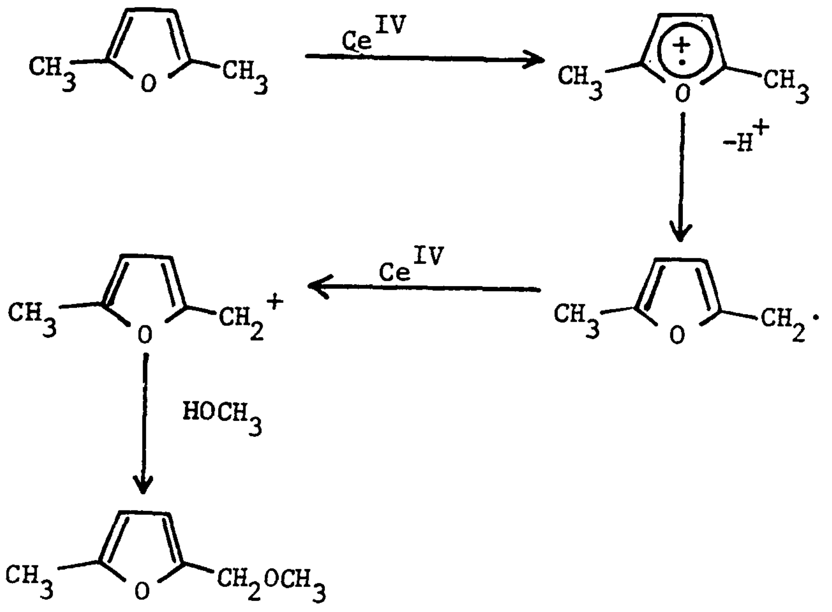
In the anodic oxidation of 2,5-dimethylfuran in which the reaction is postulated as proceeding through a radical cation intermediate, small amounts of 2-methoxymethyl-5-methylfuran and 2,5-bis(methoxymethyl)furan are generated (120, 121). These products are thought to form after proton loss by the radical cation intermediate followed by oxidation of the generated radical species to the cation followed by nucleophilic attack



Scheme 5. Abstraction mechanism for the generation of 2-methoxymethyl-5-methylfuran in the oxidation of 2,5-dimethylfuran by CAN in methanol

by methanol. It is possible to postulate a similar mechanism involving formation of a radical cation intermediate in the oxidation of 2,5-dimethylfuran by cerium(IV) (Scheme 6).

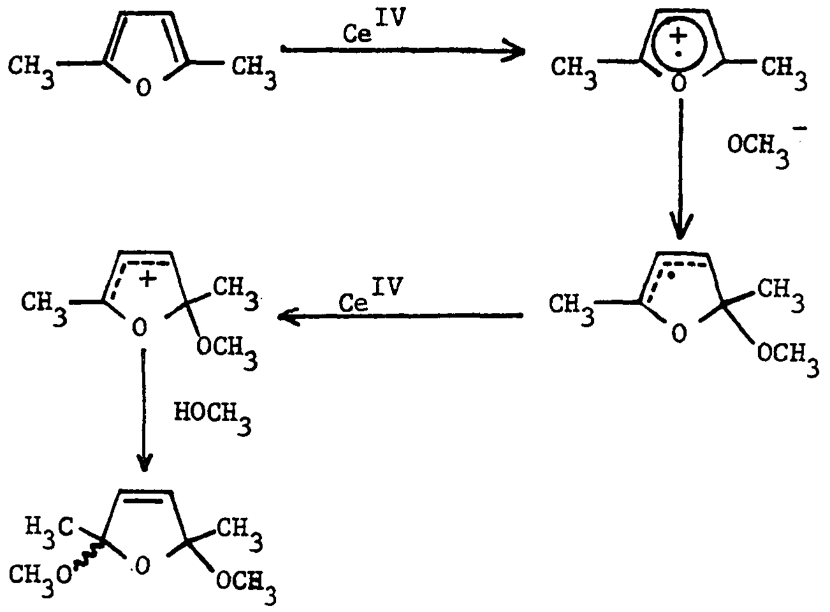
The product mixture from the oxidation of 2,5-dimethylfuran is drastically altered by the introduction of cyanide or methoxide anions. In both cases, the addition of 10 equivalents of anion per equivalent of furan generates a product mixture consisting of cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran and 2-methoxymethyl-5-methylfuran in a ration of 4:1. In the anodic oxidation of 2,5-dimethylfuran in methoxide methanol solution (117, 118) and methanol (119) similar product mixtures are obtained. The anodic oxidation of 2,5-dimethylfuran in



Scheme 6. Proposed radical cation mechanism for the generation of 2-methoxymethyl-5-methylfuran in the oxidation of 2,5-dimethylfuran by CAN

methanol with added sodium cyanide (116, 117) generates <u>cis</u> and <u>trans</u>-2-cyano-5-methoxy-2,5-dimethyl-2,5-dihydrofuran as the major products. In all these oxidations, the mechanism is assumed to involve initial oxidation of the furan nucleus to a radical cation. By analogy, the oxidation of 2,5-dimethylfuran by cerium(IV) with added cyanide or methoxide anion may also proceed through a mechanism involving formation of a radical cation intermediate.

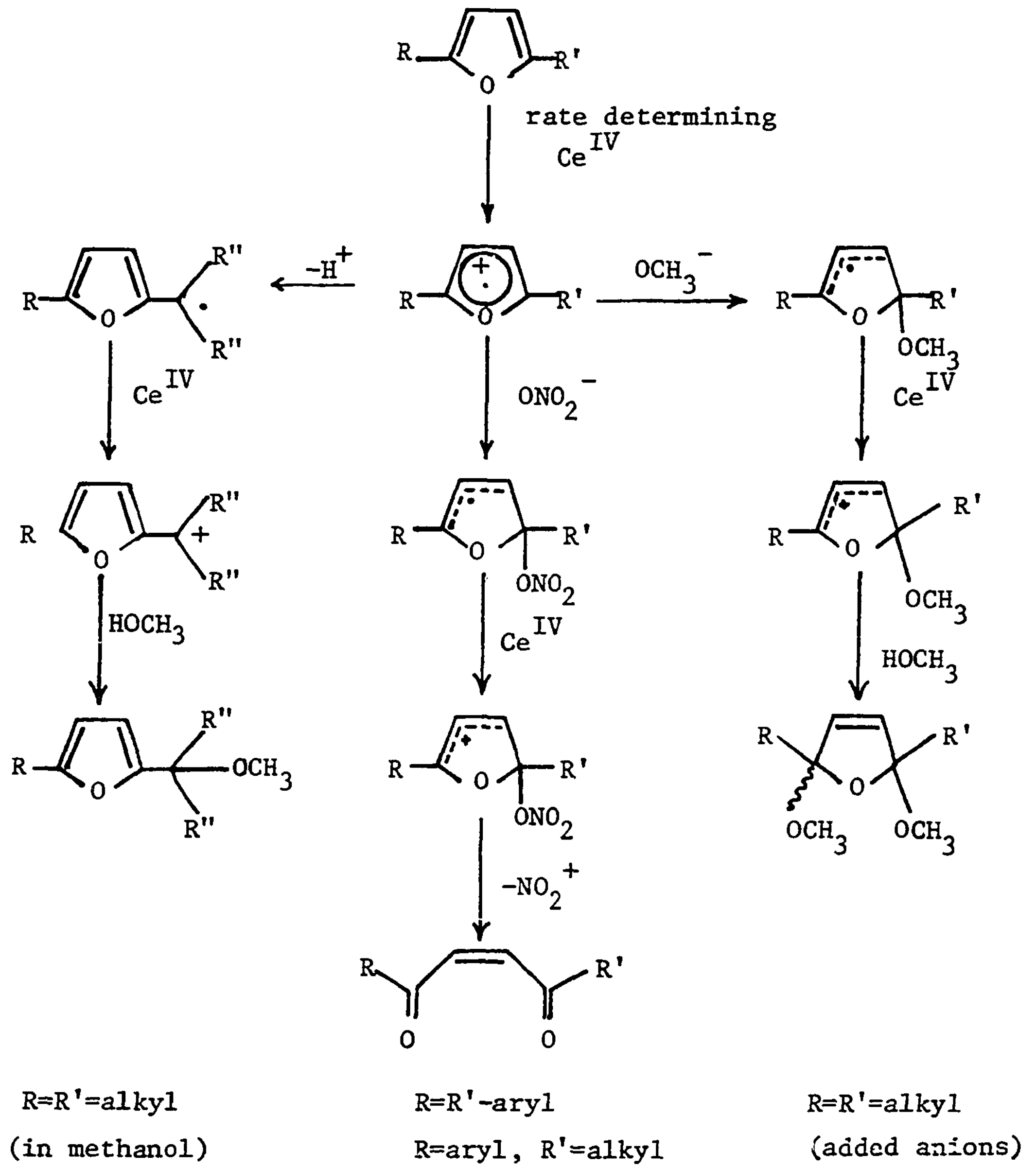
Although the products in the oxidation of 2,5-dimethylfuran in methanol with added cyanide or methoxide anions can be accounted for by a radical addition mechanism, it is difficult to rationalize why the addition of methoxide anion would so drastically alter the products formed. On the other hand, for the radical cation mechanism, if one considers the



Scheme 7. Postulated radical cation mechanism for the generation of 2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran in the CAN oxidation of 2,5-dimethylfuran in methanol with added cyanide or methoxide anions

change in nucleophilicity of the mixture with the addition of methoxide anion over methanol alone, it is possible to explain the change in products. Methoxide, being a better nucleophile than methanol, (128) is better able to trap the radical cation before proton loss occurs.

In conclusion, the oxidation of furans by cerium(IV) may be explained by the following mechanism, Scheme 8. The formation of NO_2^+ in the oxidation of 2,5-diphenylfuran by CAN is reasonable since secondary oxidation in acetonitrile has been observed. The possibility that cerium(IV) is involved is unlikely since the characteristic color of cerium(IV) solutions is absent. If 5% water is added to the reaction mixture, the secondary oxidation is suppressed while the addition of 15%



Scheme 8. Proposed mechanism for the oxidation of furans by cerium(IV)

water does not further suppress the reaction. It is possible that in acetonitrile, the NO_2^+ is able to oxidize the 2,5-diphenylfuran as postulated by Lutz and Boyer (88) while with water added, the NO_2^+ reacts with the water to generate nitric acid.

$$NO_2^+ + H_2O \longrightarrow HNO_3 + H^+$$

Synthetic Utility

The generation of cis-1,4-disubstituted-2-butene-1,4-diones in the oxidation of 2,5-diaryl or 2-aryl-5-alkylfurans by CAN is superior to previously reported methods of oxidation to the same products either in ease of work-up, ease in handling the oxidant or in isolated yield. The cis-1,4-disubstituted-2-butene-1,4-diones may be used as dienophiles for cycloaddition reactions (129, 130, 131) or as 1,3-dipolarophiles in cycloadditions (132).

Formation of 2-methoxymethyl-5-methylfuran is accomplished in one step instead of the usual two step process involving generation of 2-bromomethyl-5-methylfuran with N-bromosuccinimide followed by reaction with sodium methoxide in methanol (118). The yield of cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran is comparable to the previously reported method of reaction of 2,5-dimethylfuran with bromine in methanol (118, 133, 134). These compounds can be hydrolyzed to the cis-hexane-2,4-dione (134, 135) which could be used as a dienophile or 1,3-dipolarophile in cycloaddition reactions.

EXPERIMENTAL

Equipment

All nuclear magnetic resonance (nmr) spectra were recorded with a Varian A-60A or Perkin Elmer R-20B spectrometer. Chemical shifts are reported as δ-values in ppm from tetramethylsilane (TMS) as internal standard.

The infrared (ir) spectra were recorded with a Beckman IR-12 spectrometer.

Mass spectra were measured on an Atlas CH-4 spectrometer. High resolution mass spectra were recorded with an Associated Electronics Industries MS-902 instrument.

All melting points were determined with a Thomas Hoover Melting Point Apparatus in open capillary tubes and are uncorrected.

Gas liquid partition chromotography (glpc) analyses were performed on an Aerograph Model 200 instrument with dual thermal conductivity detectors.

Methods

Glpc analyses were carried out using a 1 m x 6.25 mm aluminum column packed with 20% SE-52 (phenyl) on Chromosorb P (80/100 mesh). Conditions for the analyses were: 200° column temperature, 275° injector temperature, 300° detector temperature and 60 ml/min helium flow. Peak areas were determined by xeroxing the chromatograms and then cutting and weighing the peaks.

In all cases the mixed solvent systems were prepared as volume percent.

Materials

Reagents and solvents were used as obtained from commercial sources unless purification procedures are noted.

Table 22. Chemicals obtained commercially

Chemical	Source
Ceric ammonium nitrate (CAN)[a]	G. F. Smith Chemical Co.
Fumaroyl chloride	Chemical Samples Co.
2,3-Dimethyl-2,3-diphenylbutane	Chemical Samples Co.
Triphenylmethane	Eastman
2,5-Dimethylfuran[b]	Chemical Samples Co.
2,5-Diphenylfuran[c]	Eastman

[a] Assumed equivalent weight of 548.

[b] Distilled before use, fraction boiling at 96-7^0/atm collected.

[c] Chromatographed on alumina with hexane as elutant before use.

Prepared Compounds

trans-1,4-Ditolyl-2-butene-1,4-dione The method of Conant and Lutz (136) was used to yield 30 g (57%) of the dione: mp 147-8^o (lit (136) 148^o); nmrδ(CDCl$_3$ 2.33 (s, 6H), 7.24 (m,4H), 7.76 (m,4H) and 7.80 (s, 2H).

2,5-Di-p-tolylfuran The procedure of Lutz and Rowlett (137) was used with 30 g trans-1,4-diphenyl-2-butene-1,4-dione yielding 22.5 g (80%) of the furan: mp 165-6^o (lit (137) 166^o); nmr (CDCl$_3$) δ 2.32 (s, 6H), 6.53 (s, 2H), 7.08 (m, 4H) and 7.52 (m, 4H).

trans-1,4-Di-(p-chlorophenyl)-2-butene-1,4-dione The procedure of Conant and Lutz (136) was used with 62 g chlorobenzene, 25 g fumaroyl chloride and 62 g aluminum trichloride to yield 24 g (46%) of the dione: mp 172-3° (lit (136) 172°); nmr ($CDCl_3$) δ 7.35 (m, 4H), 7.83 (s, 2H) and 7.87 (m, 4H).

2,5-Di(p-chlorophenyl)furan The procedure of Nowlin (138) was used on 20 g of trans-1,4-di(p-chlorophenyl)-2-butene-1,4-dione and 100 g polyphosphoric acid to yield 15 g (72%) of the furan: mp 167-8° (lit (138) 168-9°); nmr ($CDCl_3$) δ 6.63 (s, 2H), 7.28 (m, 4H) and 7.58 (m, 4H).

trans-Benzoylacrylic acid The procedure of Grummitt and coworkers (139) was used to provide 75.6 g (83%) of the acid: mp 94-5° (lit (139) 95-6°); nmr ($CDCl_3$) δ 6.89 (d, J = 16 Hz, 1H), 7.38 (m, 3H), 8.03 (d, J = 16 Hz, 1H) and 8.00 (m, 2H).

trans-1-Phenyl-4-p-tolyl-2-butene-1,4-dione Using a modification of the procedure of Lutz (140), 30 g of trans-benzoylacrylic acid in 300 ml of toluene was added 40 g phosphorus trichloride portion-wise over 30 minutes. The mixture was stirred and cooled for 1 additional hour. Then 180 g anhydrous aluminum trichloride was added and the mixture was stirred for 1 hour. The mixture was decomposed with an ice-hydrochloric acid mixture. The organic layer separated and was removed and the aqueous layer was extracted 2 times with 100 ml portions of benzene. The combined organic layers were washed with 10% aqueous sodium hydroxide solution until neutral and then 1 time with 100 ml of saturated aqueous sodium chloride solution. The organic layer was dried ($MgSO_4$) and the solvent was removed by rotary evaporation at reduced pressure. The solid residue was recrystallized from ethanol to provide 24 g (53%) of the dione:

mp 83-4°; nmr (CCl_4)δ2.42 (s, 3H), 7.40 (m, 5H), 7.93 (s, 2H), and 8.00 (m, 4H); ir (CCl_4) cm^{-1} 3070 (w), 3035 (w), 1673 (s), 1660 (s), 1608 (s), 1450 (m), 1320 (s), 1295 (s), 1235 (m), 1195 (m), 1182 (s), 1035 (m), 1025 (m) and 1018 (m); mass spectrum (70 eV) m/e (rel intensity) 250 (100), 234 (26), 119 (82), 105 (44) and 91 (13); high resolution mass spectrum calc. for $C_{17}H_{14}O_2$: 250.099372; observed: 250.096469.

2-Phenyl-5-p-tolylfuran The procedure of Lutz and Rowlett (137) was used with 21 g of trans-1-phenyl-4-p-tolyl-2-butene-1,4-dione to yield 8.5 g (43%) of the furan: mp 100-2°; nmr ($CDCl_3$) δ 2.33 (s, 3H), 6.60 (d, J = 3.2 HZ, 1H), 6.72 (d, J = 3.2 Hz, 1H), 7.20 (m, 5H) and 7.78 (m, 4H); ir (CCl_4) cm^{-1} 3035 (m), 2925 (2), 1610 (m), 1503 (s), 1485 (s), 1450 (s), 1025 (s) and 930 (m); mass spectrum (70 eV) m/e (rel. intensity) 234 (100), 129 (67), 118 (13) and 105 (6); high resolution mass spectrum calc. for $C_{17}H_{14}O$: 234.104458; observed 234.107234.

trans-p-Chlorobenzoylacrylic acid The procedure of Grummitt and co-workers (139) was used with 200 ml of chlorobenzene, 49 g malic anhydride and 132 g anhydrous aluminum trichloride to furnish 95 g (90%) of the acid: mp 153-5° (lit (141) 156°); nmr ($CDCl_3$) δ 6.77 (d, J = 16 Hz, 1H), 7.53 (m, 2H), 7.87 (d, J = 16 Hz, 1H) and 7.97 (m, 2H).

trans-1-p-Chlorophenyl-4-p-tolyl-2-butene-1,4-dione A modification of the procedure of Lutz (140) was used. To 36 g of p-chlorobenzoylacrylic acid in 450 ml of toluene was added 40 g phosphorous pentachloride. The mixture was stirred for 1.5 hours at which time 180 g anhydrous aluminum trichloride was added and the mixture was stirred at room temperature until evidence of HCl evolution had ceased. The organic layer was separated and the aqueous layer was extracted 2 times with 100 ml portions of benzene. The combined organic layers were washed with 10% aqueous sodium hydroxide solution until neutral and 1 time with 100 ml of saturated aqueous sodium chloride solution. The solvents were removed by rotary evaporation at reduced pressure and the residue was recrystallized from methanol to furnish 19.8 g (41%) of the dione: mp 142-143.5°; nmr (CCl_4) δ 2.42 (s, 3H), 7.25 (m, 4H), 7.90 (s, 2H) and 8.00 (m, 4H); ir (CCl_4) cm^{-1} 3030 (w), 1660 (s), 1605 (s), 1400 (m), 1325 (s), 1305 (s), 1190 (m), 1180 (s), 1090 (s), 1030 (m), 1010 (m) and 970 (m); mass spectrum (70 eV) m/e (rel. intensity) 285 (14.3), 283 (39.7), 139 (32), 119 (100) and 91 (23); high resolution mass spectrum calc. for $C_{17}H_{13}Cl^{35}O_2$: 284.060425; observed 284.060415: calc. for $C_{17}H_{13}Cl^{37}O_2$: 286.057475; observed 286.059061.

2-p-Chlorophenyl-5-p-tolylfuran The procedure of Lutz and Rowlett (137) was used on 17 g 1-p-chlorophenyl-4-p-tolyl-2-butene-1,4-dione to yield 11 g (69)) of the furan: mp 195-6°; nmr ($CDCl_3$) δ 2.37 (s, 3H), 6.68 (s, 2H) and 7.50 (m, 8H); ir (CCl_4) cm^{-1} 3030 (w), 1500 (s), 1480 (s), 1095 (s), 1025 (s) and 930 (m); mass spectrum (70 eV) m/e (rel. intensity) 270 (42), 268 (100); high resolution mass spectrum calc. for $C_{17}H_{13}Cl^{35}O$: 268.065487; observed 268.063589; calc. for $C_{17}H_{13}Cl^{37}O$: 270.062537; observed 270.063291.

1-Phenylpentane-1,4-dione Levulinoyl chloride was prepared by the method of Rips and coworkers (142) from 58 g levulinic acid and 61 g thionyl chloride. The acid chloride was added to 140 g anhydrous aluminum trichloride in 300 ml of benzene over 1.5 hours. The mixture was stirred a further 15 minutes and decomposed in an ice-HCl mixture. The organic layer was separated and the aqueous layer was extracted 3 times with 50 ml portions of benzene. The combined benzene layers were washed with 10% aqueous sodium hydroxide solution until neutral and 1 time with 100 ml of saturated aqueous sodium chloride solution. The benzene was removed by rotary evaporation at reduced pressure, and the residue was distilled at reduced pressure to furnish 40 g (45%) of the dione: bp 115-7°/2 mm (lit (143) 109-12°/0.35 mm; nmr (CCl_4) δ 2.02 (s, 3H), 2.60 (m, 2H), 3.03 (m, 2H), 7.20 (m, 3H), and 7.75 (m, 2H).

2-Phenyl-5-methylfuran To 40 g 1-phenylpentane-1,4-dione in 600 ml of benzene was added 6 g *p*-toluenesulfonic acid and the mixture was refluxed for 8 hours with the water generated removed with a Dean-Stark trap. The benzene solution was washed with 10% aqueous sodium hydroxide solution until neutral and 1 time with 100 ml of saturated aqueous sodium chloride solution. The benzene solution was dried ($MgSO_4$), the solvent was removed by rotary evaporation at reduced pressure and the residue was recrystallized from pentane at low temperature to yield 24.2 g (66%) of the furan: mp 40-1° (lit (144) 41-2°; nmr (CCl_4) δ 2.30 (d, J = 1Hz, 3H), 5.90 (qd, J = 1 Hz, 3 = Hz, 1H), 6.40 (d, J = 3 Hz, 1H), 7.15 (m, 3HO and 7.50 (m, 2H).

Oxidations

Competitive Oxidations

To 0.4 mmoles of each 2,5-disubstituted furan in 25 ml of acetonitrile was added 1.00 mmole of CAN in 5 ml 75% aqueous acetonitrile with rapid stirring. The mixture was allowed to stir at room temperature for 15 seconds and was quenched with 50 ml water. At this time, 0.3 mmoles of standard (2,3-diphenyl-2,3-dimethylbutane or triphenylmethane) was added to the mixture. The mixture was then extracted 3 times with

25 ml portions of benzene and the combined benzene extracts were washed 3 times with 10 ml portions of 1.2 N aqueous sodium hydroxide solution, 3 times with 25 ml portions of water and 1 time with 25 ml of saturated aqueous sodium chloride solution. The benzene solution was dried ($MgSO_4$) and the solvent was removed by rotary evaporation at reduced pressure. The residue was taken up in 6 ml of benzene for glpc analysis.

Table 23. Analyses of the competitive oxidations of 2,5-diarylfurans by CAN in 95% aqueous acetonitrile at 25°

para substituents		peak areas			mmoles	
F_1	F_2	F_1	F_2	Std.	F_1	F_2
Me, Me	Me, H[a]	0.0430	0.1143	0.2021	0.064	0.170[b]
		0.0403	0.1154	0.2293	0.058	0.167[b]
Me, H	H, H[c]	0.0883	0.1613	0.1877	0.141	0.257
		0.0883	0.1493	0.1847	0.127	0.242
Me, H	Me, Cl[a]	0.0979	0.1368	0.2121	0.137	0.193
		0.0885	0.1236	0.2053	0.131	0.183
H, H	Cl, Cl[c]	0.0708	0.1512	0.1864	0.114	0.242
		0.0782	0.1897	0.2171	0.108	0.234

[a] Triphenylmethane used as standard.

[b] 1.1 mmoles of CAN used.

[c] 2,3-diphenyl-23-dimethylbutane used as standard.

2,5-Diphenylfuran To 440.5 mg of 2,5-diphenylfuran in 15 ml of solvent was added 2.2 g CAN in 15 ml of the same solvent. The mixture was then stirred at room temperature from 5 to 30 minutes at which time the reaction was quenched with 50 ml of water. The mixture was extracted 3 times with 25 ml of ether and the combined ether extracts were washed

3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution, 2 times with 25 ml of water and 1 time with 25 ml of saturated aqueous sodium chloride solution. The ether solution was dried ($MgSO_4$), and the solvent removed by rotary evaporation at reduced pressure. The residue was then purified by recrystallization to yield from 384 - 438 mg of the dione: mp 133-4° (lit (123) 134°); nmr ($CDCl_3$) δ 7.30 (s, 2H), 7.55 (m, 6H) and 7.95 (m, 4H).

2,5-Diphenylfuran in methanol To 2.2 g of 2,5-diphenylfuran in 25 ml of methanol was added 11 g CAN in 50 ml of methanol and the reaction mixture was stirred at room temperature for 30 minutes. The mixture was poured into 300 ml of water and extracted 3 times with 100 ml of ether. The combined ether extracts were washed 3 times with 25 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 100 ml of water. The ether was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure. The residue was chromatographed on thick layer silica gel with chloroform and extracted from the silica gel with ethyl acetate. The residue was recrystallized from methanol to yield 1.50 g (60%) of 2-methoxy-1,4-diphenylbutane-1,4-dione: mp 46-8° (lit (145) 48°); nmr (CCl_4) δ 3.38 (s, 3H), 3.43 (d, J = 6.5 Hz, 2H), 5.37 (t, J = 6.5 Hz, 1H), 7.43 (m, 6H) and 7.95 (m, 4H);

2-p-Tolyl-5-phenylfuran To 468.6 mg of 2-*p*-tolyl-5-phenylfuran in 15 ml acetonitrile was added 2.1 g CAN in 5 ml of 80% aqueous acetonitrile and the reaction mixture was stirred at room temperature for 30 seconds. The reaction was quenched with 50 ml of water and the resulting mixture was extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution, 2 times with 25 ml of water and 1 time with 25 ml of saturated aqueous sodium chloride solution. The ether solution was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure. The residue was recrystallized from hexane to yield 460.3 mg (91%) of *cis*-1-*p*-tolyl-4-phenyl-2-butene-1,4-dione: mp 109-10^{o}; nmr ($CDCl_3$) δ 2.30 (s, 3H), 7.02 (s, 2H), 7.21 (m, 5H) and 7.75 (m, 4H); ir (CCl_4) cm^{-1} 3090 (w), 3070 (w), 3040 (w), 1675 (s), 1613 (s), 1452 (m), 1410 (m), 1395 (m), 1240 (s), 1180 (s) and 1020 (m); mass spectrum (70 eV) *m/e* (rel. intensity) 250 (100), 119 (76), 105 (47), 91 (26) and 76 (21); high resolution mass spectrum calc. for $C_{17}H_{14}O_2$: 250.09937; observed 250.097783.

2,5-Di-p-tolylfuran To 248.3 mg of 2,5-di-*p*-tolylfuran in 20 ml of 95% aqueous acetonitrile was added 1.1 g CAN in 95% aqueous acetonitrile and the mixture was stirred at room temperature for 30 seconds. The reaction was quenched with 50 ml of water and the resulting mixture was extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml 1.2 N aqueous sodium hydroxide solution, 2 times with 25 ml of water and 1 time with 25 ml of saturated aqueous sodium chloride solution. The ether solution was dried ($MgSO_4$) and the ether was removed at reduced pressure on a rotary evaporator. The residue was recrystallized from hexane to yield 245.3 mg (88%) of *cis*-1,4-di-*p*-tolyl-2-butene-1,4-dione: mp 123-4^{o} (lit (136) 134^{o}); nmr ($CDCl_3$) δ 2.33 (s, 6H), 7.06 (s, 2H), 7.10 (m, 4H) and 7.82 (m, 4H).

2-Phenyl-5-methylfuran in 95% aqueous acetonitrile To 1.6 g of 2-phenyl-5-methylfuran in 10 ml 95% aqueous acetonitrile was added 11 g CAN in 40 ml 95% aqueous acetonitrile and the mixture was stirred at room temperature for 1 hour. The mixture was poured into 300 ml of water and extracted 3 times with 100 ml of ether. The combined ether extracts were washed 3 times with 25 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with water. The ether solution was dried ($MgSO_4$) and the ether was removed by rotary evaporation at reduced pressure. The residue was chromatographed on thick layer silica gel with chloroform and extracted from the silica gel with ethyl acetate to yield 1.04 g *cis*-1-phenyl-2-pentene-1,4-dione: nmr (CCl_4) δ 2.13 (s, 3H), 6.38 (d, J = 12 Hz, 1H), 6.76 (d, J = 12 Hz, 1H), 7.40 (m, 3H) and 7.95 (m, 2H); ir (CCl_4) cm^{-1} 2960 (m), 1710 (s), 1675 (s), 1620 (m), 1450 (m), 1390 (m), 1360 (m), 1300 (m), 1250 (m), 1182 (m), 1175 (m) and 870 (s); mass spectrum (70 eV) *m/e* (rel. intensity) 174 (38), 159 (49), 131 (45), 105 (71) and 77 (100); high resolution mass spectrum calc. for $C_{11}H_{10}O_2$: 174.068074; observed 174.068793.

2-Phenyl-5-methylfuran in methanol To 1.6 g 2-phenyl-5-methylfuran in 10 ml methanol was added 11 g of CAN in 40 ml methanol and the reaction mixture was stirred at room temperature for 15 minutes. The reaction mixture was poured into 300 ml of water and extracted 3 times with 100 ml of ether. The combined ether extracts were washed 3 times with 25 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with water. The ether solution was dried ($MgSO_4$) and the ether was removed by rotary evaporation at reduced pressure. The residue was chromatographed on thick layer silica gel with benzene and extracted from the silica gel with ethyl acetate to yield 1.03 g (50%) of 3-methoxy-1-phenylpentane-1,4-dione: nmr (CCl_4) δ 2.18 (s, 3H), 3.19 (d, J = 6Hz, 1H), 3.20 (d, J = 5 Hz, 1H), 4.13 (dd, J = 5 Hz, J = 6Hz; 1H), 7.35 (m, 3H) and 7.85 (m, 2H); ir (CCl_4) cm^{-1} 2940 (w), 1720 (s), 1695 (s), 1600 (m), 1450 (m), 1355 (m) and 1120 (s); mass spectrum (70 eV) m/e (rel. intensity) 206 (2), 174 (100), 158 (40), 128 (38) and 105 (100); high resolution mass spectrum calc. for $C_{12}H_{14}O_3$: 206.094286; observed: 206.094286.

2,5-Dimethylfuran in methanol To 0.4 g 2,5-dimethylfuran in 10 ml of methanol was added 4.4 g CAN in 20 ml of methanol and the reaction mixture was stirred at room temperature for 30 minutes. The mixture was poured into 50 ml of water and extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 25 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed by rotary evaporation at reduced pressure to yield 0.40 g (60%) of 2-methoxymethyl-5-methylfuran: nmr (CCl_4) δ 2.25 (s, 3H), 3.20 (s, 3H), 4.18 (s, 2H), 5.78 (m, 1H) and 6.02 (d, J = 3Hz, 1H); ir (CCl_4) cm^{-1} 2990 (s), 2940 (s), 2840 (m), 1380 (m), 1175 (s), 1100 (s), 950 (s) and 890 (s).

2,5-Dimethylfuran with added sodium methoxide in methanol To 0.4 g 2,5-dimethylfuran and 2.2 g sodium methoxide in 25 ml of methanol was added 4.4 g CAN in 20 ml methanol. The reaction mixture was stirred at room temperature for 30 minutes and poured into 50 ml of water. The mixture was extracted 3 times with 25 ml of ether and the combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 25 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure. The residue was chromatographed on thick layer silica gel with benzene to yield 477 mg (75%) of cis and trans-2,5-dimethyl-2,5-dihydrofuran (118) nmr (CCl_4) δ 1.38 (s, 6H), 1.47 (s, 6H), 3.11 (s, 6H), 3.20 (s, 6H) and 5.77 (s, 2H).

2,5-Dimethylfuran with added sodium cyanide in methanol To 0.4 g of 2,5-dimethylfuran and 2.4 g sodium cyanide in 25 ml of methanol was added 4.4 g CAN in 20 ml methanol and the reaction mixture was stirred at room temperature for 30 minutes. The reaction mixture was poured into 50 ml of water and extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 25 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure. The residue was chromatographed on thick layer silica gel with benzene to yield 489 mg (78%) of cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran (118): nmr (CCl_4) δ 1.38 (s, 6H), 1.47 (s, 6H), 3.11 (s, 6H), 3.20 (s, 6H) and 5.77 (s, 2H).

ESR experiment A 0.5 M solution of 2,5-diphenylfuran in 95% aqueous acetonitrile and a 0.2 M solution of CAN in 95% aqueous acetonitrile were prepared and degassed with nitrogen for 15 minutes. Equal volumes of the two solutions were then flowed into an efficient mixing chamber and into an esr cell. A spectrum was observed, but it could not be interpreted.

PART III

REACTIONS OF CERIC AMMONIUM NITRATE WITH OLEFINS

SUMMARY OF PART III

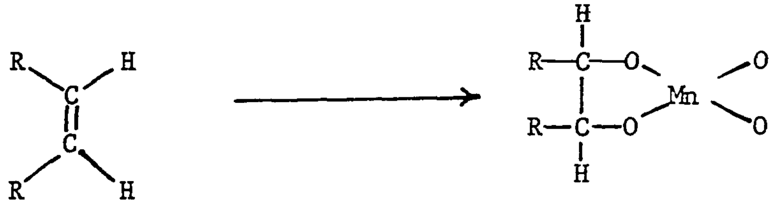
The oxidation of phenylsubstituted olefins has been found to yield 1,2-dinitrate and 1-acetamido-2-nitrate products when the oxidation with ceric ammonium nitrato (CAN) is performed in acetonitrile, the products observed are 1,2-dinitrato and 1-hydroxy-2-nitrato products or secondary oxidation products of the hydroxy nitrate.

The formation of the dinitrate has been found to occur stereospecifically by a trans-addition in the case of indene, trans-stilbene and cis-stilbene. The oxidation of trans-β-methylstyrene also appears to proceed stereospecifically to a single isomer, which by analogy with the behavior of the stilbene system has tentatively been identified as erythro-1,2-n-propylbenzenediol-1,2-dinitrate. Evidence is presented for the formation of bridging nitrate intermediate to explain the stereospecificity of the product formation.

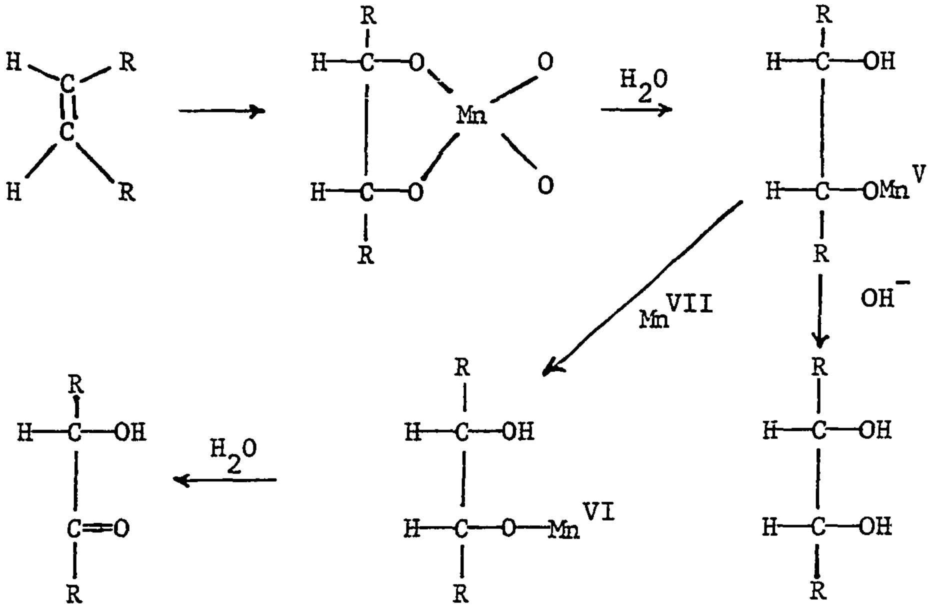
HISTORICAL

Permanganate Oxidations

The oxidation of olefins to glycols with permanganate has long been known. The mechanism of the oxidation was postulated as proceeding through a cyclic manganic ester as the addition of the hydroxyl groups is cis. This was shown by the generation of meso-tartaric acid from maleic acid and d,l-tartaric acid from fumaric acid (146, 147) Wiberg and Saegebarth (148) later confirmed the presence of a cyclic manganese ester by the use of oxygen—18 and showed that oxygen was transferred from the



permanganate to the substrate. Wiberg and Saegebarth (148) postulated the following mechanism for the olefin oxidation by permanganate.



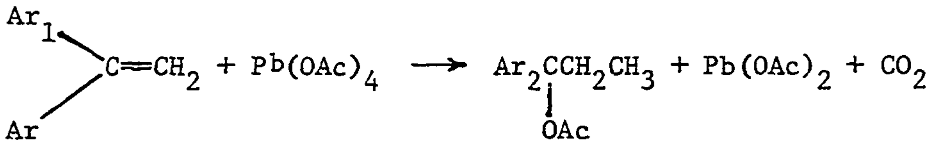
If electron withdrawing groups are present on an alkene, the oxidation appears to be facilitated. Fluoroolefins, for example, are rapidly degraded and cleaved (149, 150) while in steroids, cyano alkenes give good yields of α-hydroxy ketones (151).

Lead Tetraacetate

The oxidation of aliphatic or cyclic olefins can be oxidized to 1,2-diacetoxy compounds in low yields (151). Electron donors at the double bond makes the addition easier as enols and enol ethers react under mild conditions (152, 153, 154).

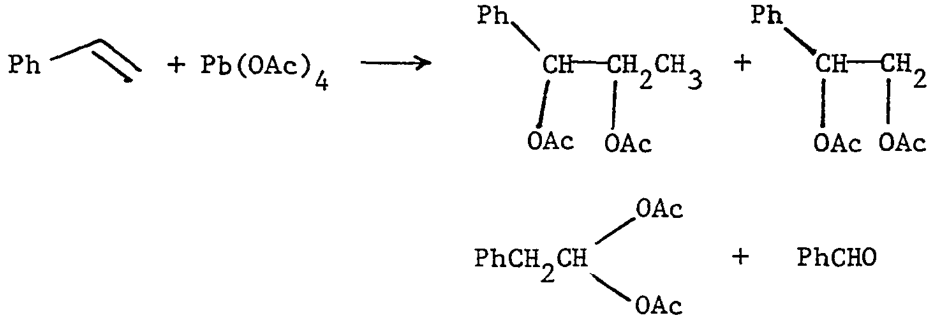
The oxidation of olefins by lead tetraacetate (LTA) does not seem to be stereoselective as most olefins give both possible isomers. In the case of indene, 1,2-dihydronaphthalene and dioxene, however, the oxidations gave predominantly the trans addition product (151). The oxidation of ergosterol by LTA yielded pure cis addition (155).

The oxidation of substituted styrenes by LTA has been studied by a number of workers. Criegee and coworkers (153) oxidized styrene and 1,1-diphenylethylene and isolated products that indicated that the



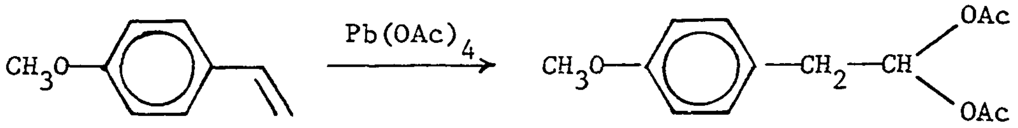
$$\mathrm{{}^{Ar_1}_{Ar}{>}C{=}CH_2 + Pb(OAc)_4 \longrightarrow Ar_2\underset{\overset{|}{OAc}}{C}CH_2CH_3 + Pb(OAc)_2 + CO_2}$$

addition of a methyl and acetoxy group to the double bond had occurred. Later, Norman and Thomas (156) re-examined the oxidation of styrene with LTA and isolated four products. It was found that the relative yields of the first three products are strongly dependent on the reaction conditions. These results, coupled with kinetic evidence, indicated



that the formation of the first product resulted from a radical chain reaction, the third from a heterolytic process and the second from two concurrent heterolytic and homolytic reactions.

The reaction of p-methoxystyrene (153) with LTA occurs at room



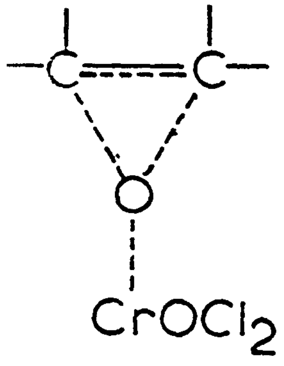
temperature to give a 90% yield of p-methoxyphenylacetaldehyde diacetate. The ortho compound gave a 64% yield of the corresponding product. Migration of the aryl group was ascertained through product studies using α-methyl-p-methoxystyrene and 1,1-di(p-methoxyphenyl)ethylene. Further conformation of the aryl migration was obtained by Yukawa and Hayashi (157) by using isotopically labeled olefin.

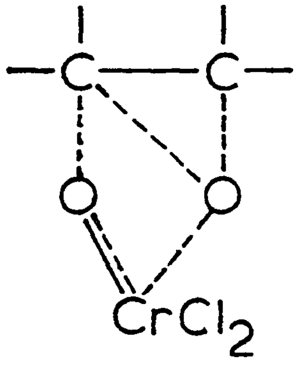
Norman and Thomas (158) have studied the reaction of LTA with α-methylstyrene and cis and trans-β-methylstyrene. In the case of α-methylstyrene, the heterolytic reaction is more important than the similar reaction for styrene. For the β-methylstyrenes, both reactions are much slower than for styrene. Further, in the heterolytic reaction, for α-methylstyrene, migration of the phenyl group predominates over formation of an acetoxonium ion while for β-methylstyrenes, the acetoxonium ion formation predominates. In the formation of 1,2-diacetates in the *cis* and *trans*-β-methylstyrene oxidations the addition occurs mainly *cis*, as *threo*-2-phenylpropane-1,2-diol diacetate predominates in the oxidation of *trans*-β-methylstyrene while *erythro*-2-phenylpropane-1,2-diol diacetate predominates in the oxidation of *cis*-β-methylstyrene.

The lead(IV) oxidation of 3-anisyl-3,3-diphenylpropene and 2-methyl-3-anisyl-3-3-diphenylpropene was studied by Norman and Thomas (159). It was found that 3-anisyl-3,3-diphenylpropene reacts exclusively with aryl migration while under the same conditions, 2-methyl-3-anisyl-3,3-diphenylpropene does not react. Evidence was obtained for a lead-olefin complex with the latter olefin.

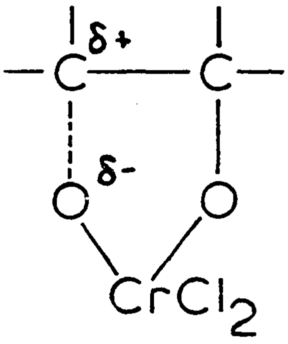
Chromium

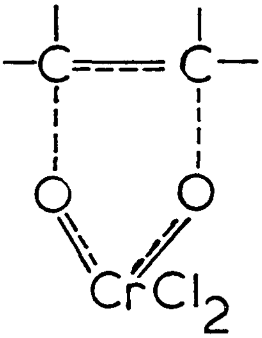
The oxidation of alkenes by chromyl chloride has recently been extensively studied by Freeman and coworkers (160, 161, 162, 163, 164, 165). Freeman and Yanachika (162) oxidized cyclopentene, cyclohexene and norbornene with chromylchloride and a comparison of the relative rates was made, with the relative rates of other cycloalkene reactions involving cyclic activated complexes. From these comparisons, the activated complexes for the oxidation of cyclopentene or cyclohexane was represented



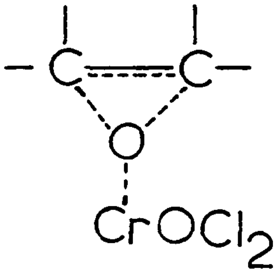


by either species shown above while the activated complex in the norbornene oxidation may be represented by the species below.



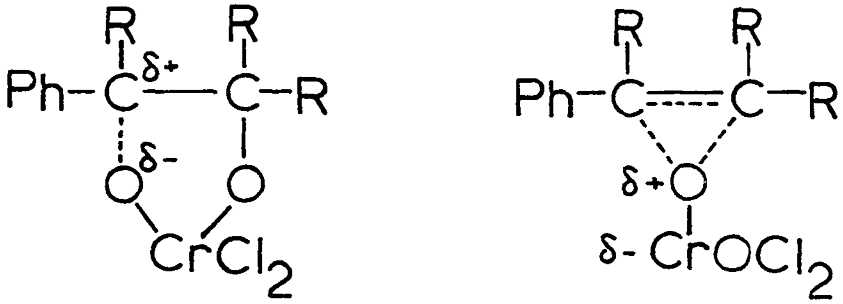


In the oxidation of alkenes, Freeman and coworkers (164) found that the chromyl chloride oxidation was only slightly affected by steric factors. A study of the activation parameters showed low enthalpies of activation and large negative entropies of activation. A Taft correlation was obtained with a $\rho = -2.63 \pm 0.17$ indicating some carbenium ion character in the activated complex. From a comparison of the relative reactivities of chromyl chloride oxidations with other electrophilic alkene reactions, the rate determining step of the reaction involves cyclic three membered activated complex.



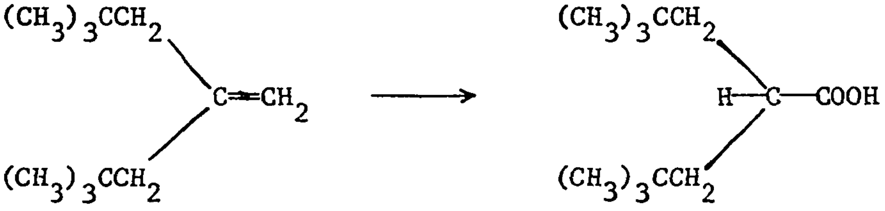
Freeman and Yamachika (163, 165) have oxidized a series of substituted styrenes with chromyl chloride and obtained a Hammett correlation with

$\rho = -1.99$. The enthalpies of activations, entropies of activation and relative rates of oxidations were consistent with an activated complex involving a partially positive charged benzylic carbon atom in a cyclic



epoxide or a partly bridged resonance-stabilized five membered ring. The products in this reaction as in the others were aldehydes or ketones.

The chromic acid oxidation of olefins produces several different products, among them epoxides, glycols and cleavage products (166, 167, 168). Rearrangements may also occur in the reaction to give carboxylic acids (169). A similar product is obtained in the oxidation of tetramethylethylene which gives t-butylmethylketone (166).



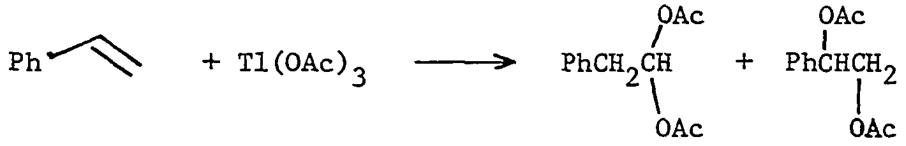
Recently, Awasthy and Rocek (170) oxidized a series of olefins to determine the nature of the activated complex in the oxidation by chromic acid. It was found that the rate of oxidation was determined primarily by the number of alkyl substituents rather than by their position on the double bond. Further, the relative rates of the oxidation of cyclopentene, cyclohexene and norborene are consistent with formation of a

3 member cyclic activated complex. The authors conclude that the chromic acid oxidation of an olefin is a symmetric electrophilic attack of chromium on the double bond generating an epoxide as an intermediate.

The oxidation of alkenes with chromyl acetate leads to epoxides in most cases and has been extensively studied by Hickinbottom and coworkers (171, 172, 173, 174, 175). When cycloalkenes are oxidized with chromyl-trichloroacetate in acetone-carbon tetrachloride solution good yields of cleavage products the dialdehydes were found (176). When the substrate in the chromyl acetate oxidations are tetraphenylethylenes, the major product is found to be the carbonate. The carbonate is formed by oxidations of the ethylenic species generated by proton loss from the bridged acetoxy cation. Thus, with tetraphenylethylene, the chromyl acetate oxidation generates benzopinacol carbonate in 60% yield (177). Recently, alkenes have been oxidized with bis(triphenylsilyl)chromate to yield cleavage products, aldehydes and ketones. The reaction is thought to proceed through a concerted mechanism after formation of a chromate ester.

Thallium

The oxidation of alkenes by thallium(III) has been studied only to a limited extent. Kabbe (178) found the thallium(III) acetate is intermediate between mercury(II) acetate and lead(IV) acetate. The oxidation of styrene yielded 2-phenyl-1,1-ethanediol diacetate and



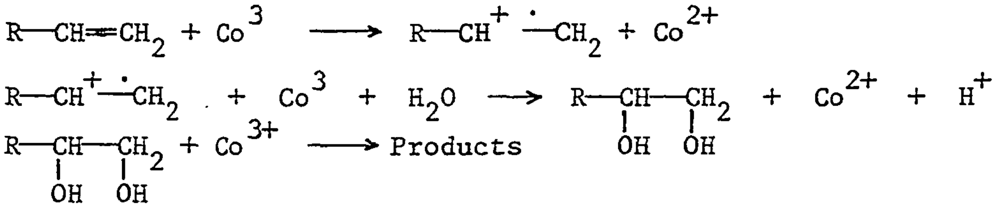
1-phenyl-1,2-ethanediol diacetate while the oxidation of p-methoxystyrene yielded only 2-(p-methoxyphenyl)-1,1-ethanediol diacetate.

Pande and Winstein (179) studied the oxidation of norbornene and norbornadiene with thallium(III) acetate. In both oxidations organothallium species were isolated and identified. The products in the reaction, resulting from "dethallation" have been identified as diacetates in all cases which are postulated as arising from monoacetoxy substituted carbonium ions.

The oxidation of substituted styrenes with thallium(III) acetate was later studied by Ouellette and coworkers (180). The rate of oxythallation of styrenes was found to be second order, first order in each reactant. A Hammett correlation was obtained with $\rho = -2.2$ which indicates the carbenium ion character in the reaction is approximately the same as oxymercuration. A correlation of the log of the product ratio, 2-aryl-1,1-ethanediol diacetate:1-aryl-1,2-ethanediol diacetate, with Brown σ^+ values was found with $\rho = -1.7$. This effect of styrene structure on the product distribution indicates that the decomposition of the oxythallation adduct proceeds through a carbenium ion.

Cobalt

Cobalt has been found to oxidize alkenes in a second order reaction, first order in both reactants by Bawn and Sharp (181, 182). The oxidation was postulated as proceeding through radical cation formation



$$\mathrm{R{-}CH{=}CH_2 + Co^{3} \longrightarrow R{-}CH^{+}{-}\dot{C}H_2 + Co^{2+}}$$

$$\mathrm{R{-}CH^{+}{-}\dot{C}H_2 + Co^{3} + H_2O \longrightarrow R{-}\underset{OH}{CH}{-}\underset{OH}{CH_2} + Co^{2+} + H^{+}}$$

$$\mathrm{R{-}\underset{OH}{CH}{-}\underset{OH}{CH_2} + Co^{3+} \longrightarrow Products}$$

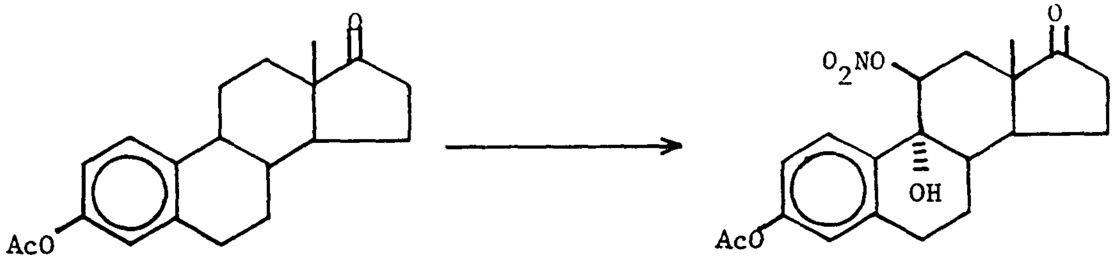
as the rate determining step. Recently Dessau (183) has provided substantiation to this mechanism by observing a series of olefin radical cations by esr with Cobalt(III) acetate in trifluoroacetic acid with 10% borontrifluoride in acetic acid in a flow system.

Cerium

The oxidation of 1,3,5-cycloheptatriene with ceric ammonium nitrate in acetic acid was shown to yield benzaldehyde, benzene and carbon monoxide by Trahanovsky and coworkers (122). Evidence supporting the intermediacy of the tropylium ion in the oxidation was presented.

Recently the oxidation of olefins by ceric carboxylates was found by Heiba and Dessau (184) to provide good yields of lactones. The reaction was found to proceed through a non-decarboxylative pathway involving carboxyalkyl radicals in the thermal decomposition of ceric carboxylates. In the photochemical decomposition, however, decarboxylation occurred to generate alkyl radicals and carbon dioxide.

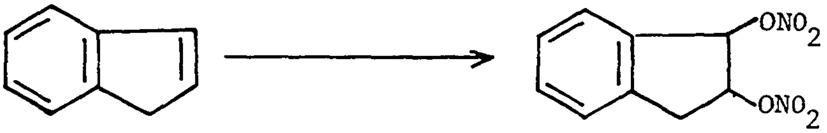
Recently, Sykes and Rutherford (185) have found that the oxidation of oestrone acetate with ceric ammonium nitrate in 90% aqueous acetic acid gave 9 α, 11β -diol-11-nitrateoestroneacetate stereospecifically in 69% yield.

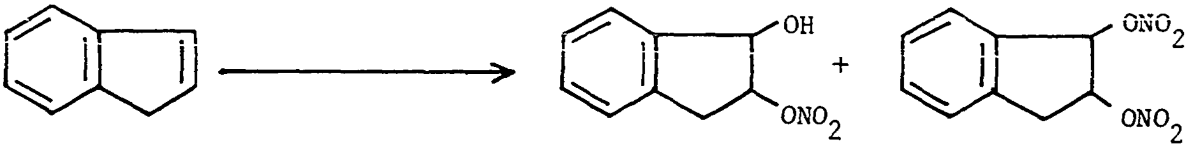


Muller and coworkers (123) recently examined the oxidation of a series of olefins with ceric ammonium nitrate and reported that CAN does not react with carbon hydrogen bonds but with the non-aromatic carbon-carbon double bond. A mechanism is proposed involving radical addition of nitrate to the double bond in the rate determining step.

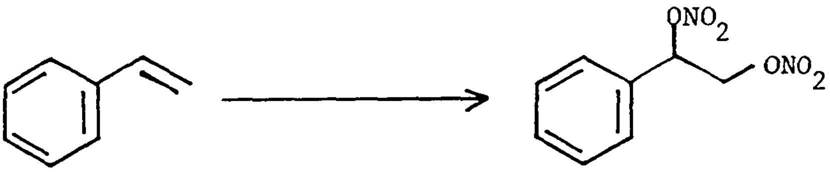
RESULTS

The oxidation of olefins by ceric ammonium nitrate (CAN) has been studied in two different solvent systems, acetonitrile and 50% aqueous acetonitrile. In acetonitrile, the products generated are 1,2-dinitrates and 1-acetamido-2-nitrates, in yields ranging from fair to good. Thus, when indene was oxidized in acetonitrile, the product isolated was 1,2-indandiol-1,2-dinitrate while the oxidation of indene in 50% aqueous acetonitrile yielded approximately a 50-50 mixture of 1,2-indandiol-1,2-dinitrate and 1,2-indandiol-1-nitrate.

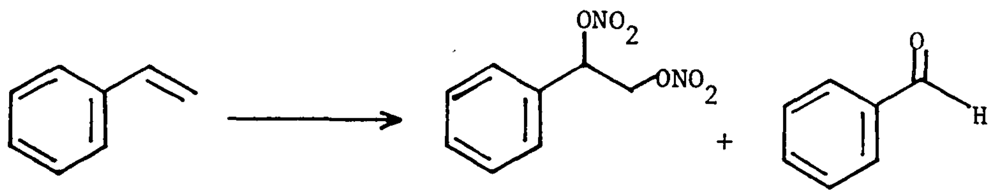




If styrene is used as substrate, the reaction in acetonitrile yields

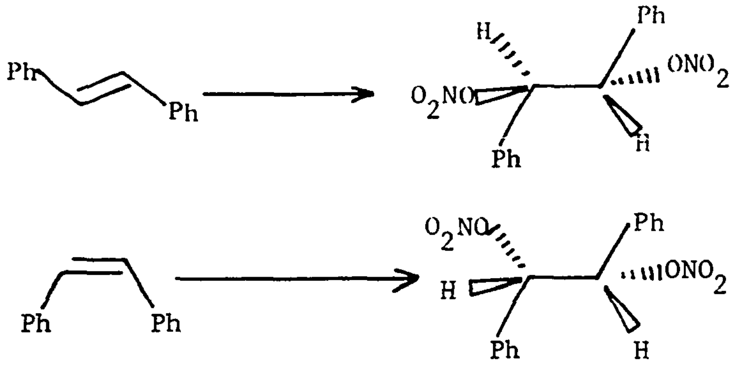


1,2-styrenediol-1,2-dinitrate. If the reaction is performed in 50% aqueous acetonitrile, a product mixture is generated which includes:



1,2-styrenediol-1,2-dinitrate and benzaldehyde.

The oxidation of *trans*-stilbene in acetonitrile generated the *meso*-1,2-stilbenediol-1,2-dinitrate while the oxidation of *cis*-stilbene generates *d*,*l*-stilbenediol-1,2-dinitrate. In both reactions nitrato acetamides are produced and, while the stereochemistry of these products

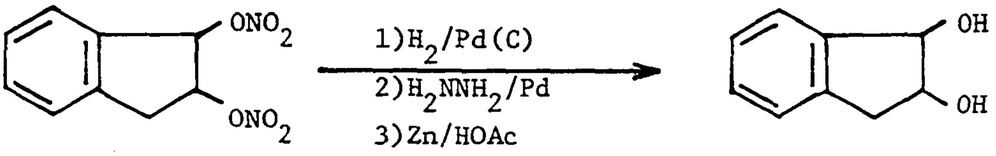


is unknown, the nmr spectra indicate only one of the two possible isomers is formed in each case.

The oxidation of *trans*-β-methylstyrene also produced a mixture of

1,2-n-propylbenzenediol-1,2-dinitrate and N-(2-nitrato-1-phenylpropyl)-acetamide. Again, by nmr, the spectrum indicates only one of the two possible isomers. By analogy with the stilbene system, one would predict that the erythro product is formed.

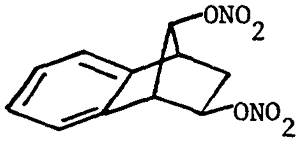
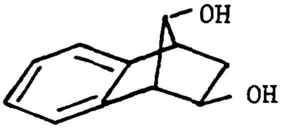
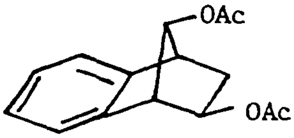
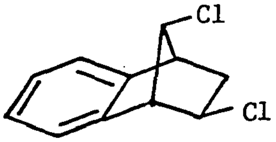
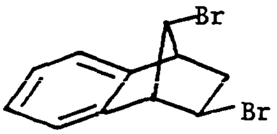
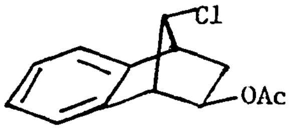
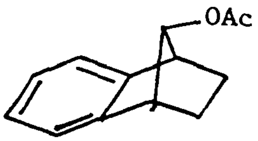
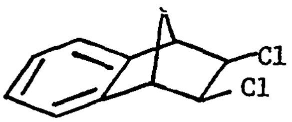
The stereochemistry of 1,2-indandiol-1,2-dinitrate produced in the oxidation of indene was determined by reduction of the dinitrate to the diol using: 1) hydrogenation over 10% palladium on charcoal; 2) hydrazine



with 10% palladium on charcoal and 3) zinc and acetic acid. A comparison of the spectral properties, melting point and mixed melting point of the diol from the reductions with trans-1,2-indandiol (186) showed the compounds to be identical.

The oxidation of benzonorbornadiene by CAN was studied only in acetonitrile. The major product has been identified as exo-2-anti-7-benzonorbornene. The stereochemistry was determined by reduction with lithium aluminum hydride to the dialcohol and converting the dialcohol to the corresponding diacetate and acetonide which were identified by spectral properties. A comparison of the nmr spectra with published spectra (187, 188, 189) of similar compounds was consistent with the above structures (Table 24).

Table 24 . Nmr spectra of substituted benzonorbornenes

Compound[a]	H_1	H_4	H_{5x}	H_{5n}	H_{7a}	H_{7s}
	3.56[b]	3.89	ONO_2	4.80	ONO_2	5.02
	3.30[b]	3.30	OH	3.98	OH	4.10
	3.34	3.67	OAc	4.57	OAc	4.57
	3.40	3.54	Cl	3.73	Cl	3.97
	3.48	3.85	Br	3.70	Br	4.10
	3.37	3.52	OAc	4.56	Cl	3.98
					OAc	4.47
	3.45	3.45	Cl	3.99	2.53	1.99

[a] All spectra run in CCl_4, unless noted.

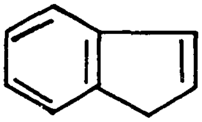
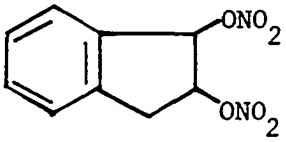
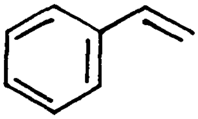
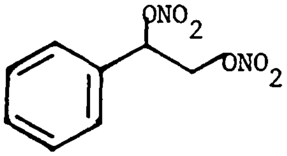
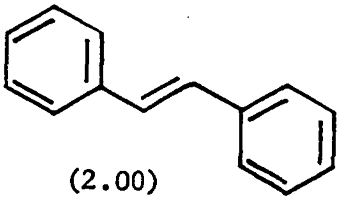
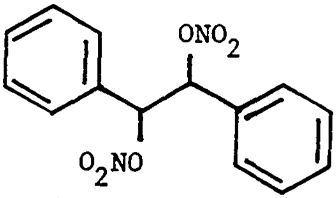
[b] $CDCl_3$ solvent.

Other compounds which have been found to undergo oxidation by CAN are norbornene, norbornadiene, alpha-pinene, beta-pinene, methylenecyclohexane, 1-methylcyclohexene, dibenzobarralene, acenaphthalene, and 2-methylpentene. Olefins which were recovered unchanged after reaction were phenylacetylene, 1-octene, 1,5-cyclooctadiene, 1,3-cyclooctadiene and tert-butylethylene.

In Table 25 are listed some olefins for which the products have been characterized and absolute yields determined. Two equivalents of CAN in acetonitrile were added to the olefin in acetonitrile and the mixture was then allowed to stir at room temperature or refluxed until the mixture had faded from orange to pale yellow and precipitation of cerium(III).

The characterization of the 1,2-dinitrate products was performed by high resolution mass spectroscopy as the CHN analyses, except for 1,2-styrenediol-1,2-dinitrate and 2,7-benzonorbornenediol-2,7-dinitrate, were unacceptable. The same problem arose for the 1,2-indandiol-2-nitrate as the characterization was accomplished by high resolution mass spectrometry.

Table 25. Absolute yields of 1,2-dinitrates from the oxidation of olefins with CAN in acetonitrile

Substrate (mmoles)	Product	Yield[a] %
 (2.00)		$70.3 \pm 2.6^{b,c}$
 (2.00)		$50.5 \pm 0.2^{b,d}$
 (2.00)		$55.5 \pm 2.2^{e,f}$

[a] Standard deviations based on 3 independent runs.

[b] Yields based on nmr analysis of unpurified products using dibenzylether as standard.

[c] Reaction run at 25 ± 3° for 30 minutes.

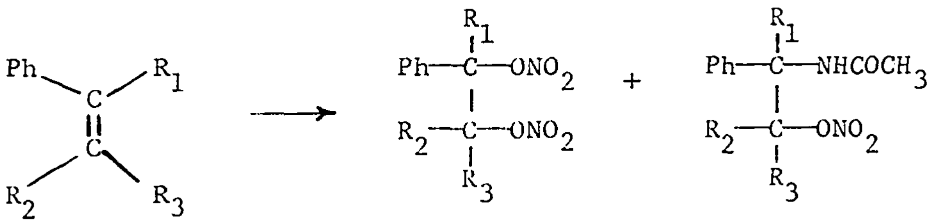
[d] Reaction run at 80 ± 3° for 45 minutes.

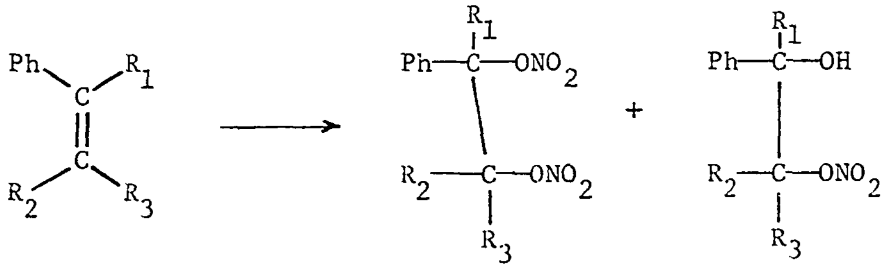
[e] *p*-Chlorotoluene used as standard.

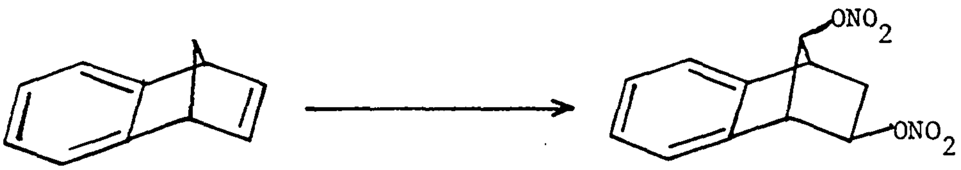
[f] Reaction run at 80 ± 3° for 15 minutes.

DISCUSSION

The oxidation of phenyl substituted olefins by ceric ammonium nitrate (CAN) has been found to yield 1,2-dinitrate products and in some cases, 1-acetamido-2-nitrato products in acetonitrile. In 50% aqueous acetonitrile, the nitrato acetamide is no longer formed and a 1-hydroxy-2-nitrate product is found. The oxidation of benzonorbornadiene in acetonitrile has been found to lead to rearranged <u>exo</u>-2-<u>anti</u>-7-dihydroxybenzonorbornene-2,7-dinitrate.







The formation of the nitrate acetamide and nitrate alcohol products can best be accounted for by trapping of a cationic species by acetonitrile and water, respectively. In the case of the dinitrates, however, the possibility exists for the second nitrate to be introduced through either a ligand transfer oxidation or by electron transfer followed by nucleophilic attack on the generated electron deficient species by nitrate anion (190, 191). The oxidation of benzonorbornadiene supports the oxidation by electron transfer as rearrangements in the norbornene, norbornadiene, and benzonorbornene systems are known to occur *via* carbonium ion intermediates (192).

The oxidation of indene, *trans*-β-methylmethylstyrene, *cis*-stilbene and *trans*-stilbene has been found to proceed stereospecifically by *trans* addition of the nitrate groups across the double bond. The stereochemistry of the addition in the oxidation of indene was determined by reduction of the dinitrate to 1,2-indandiol which was identical in all respects to an authentic sample of *trans*-1,2-indandiol (186).

The product from the oxidation of *trans*-stilbene has been identified as *meso*-1,2-stilbenediol-1,2-dinitrate by comparison with an authentic sample.[1] The oxidation of *cis*-stilbene was found to yield

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[1] Prepared by M. D. Robbins.

d,l-1,2-stilbenediol-1,2-dinitrate while the oxidation of trans-β-methylstyrene yielded only one of two possible isomers, which by analogy with the behavior of the styrene system has been tentatively identified as erythro-1,2-n-propylbenzenediol-1,2-dinitrate. The evidence for the formation of only one isomer in the oxidation of trans-β-methylstyrene is found in a comparison of the nmr spectra of the product from the oxidation of trans-β-methylstyrene with CAN and the oxidation of azide anion with CAN in the presence of trans-β-methylstyrene (193). The methyl signal for the product in the oxidation of trans-β-methylstyrene with CAN shows a doublet for the methyl resonance while the nmr of the products in the oxidation of azide with CAN in the presence of trans-β-methylstyrene shows two doublets for the methyl resonances, as would be expected if both erythro and threo isomers are generated. In the oxidation of bromide anion with CAN in the presence of trans-β-methylstyrene (194), only one of two possible isomers is generated. Bridging by bromine has been postulated both for radical intermediates (195, 196, 197) and cationic intermediates (198).

The stereospecificity of the oxidation of cis and trans-stilbenes by CAN indicates that after addition of the first nitrate group to the double bond, there is restricted rotation about the central carbon-carbon bond of the generated species. A reasonable explanation for the restricted rotation is the formation of a bridged nitrate intermediate. Involvement of the nitrate could occur at either a radical or cationic stage of the reaction. Bridged radical species have been postulated (195, 196, 197) and the intermediacy of a bridged nitrate radical would be sufficient to explain the stereospecific formation of meso-1,2-

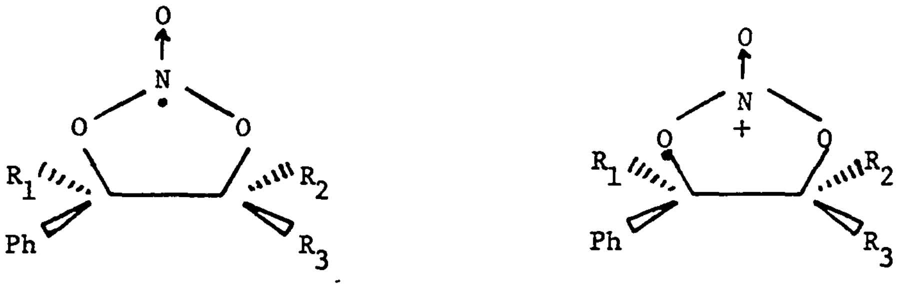
stilbenediol-1,2-dinitrate from trans-stilbene and d,l-1,2-stilbenediol-1,2-dinitrate from cis-stilbene in the CAN oxidations.

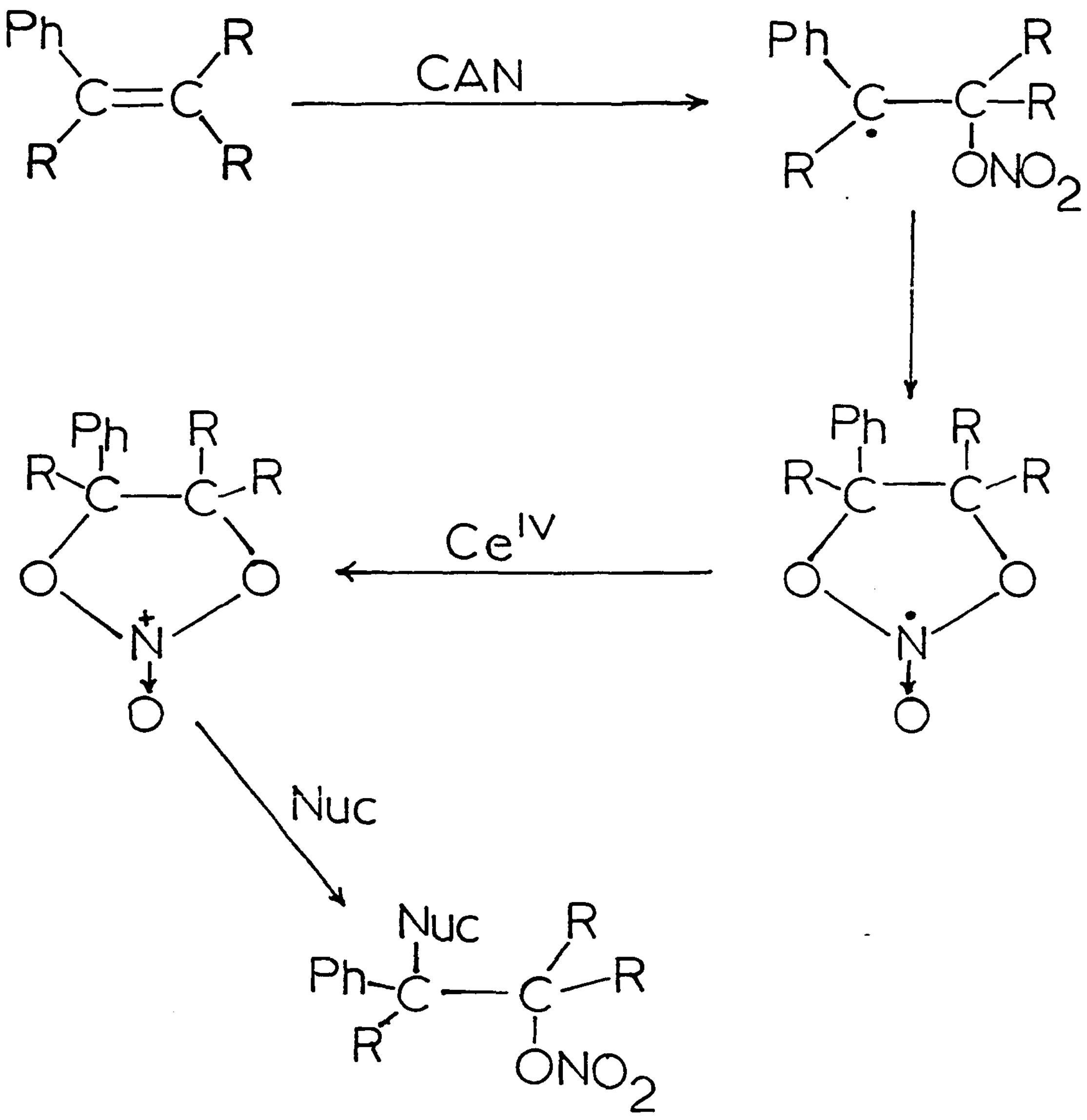
The possibility of bridging nitrate in cationic species has generally been discounted. Fishbein (199) found that in the reaction of silver nitrate with isomeric 2,3-dibromobutanes, the first halogen was displaced with retention of configuration presumably due to neighboring bromine participation. The second bromine was displaced with inversion which was taken to indicate little or no participation by neighboring nitrate. Hayward and coworkers (200) studied the reaction of meso-1,2-dibromostilbene with silver nitrate and isolated only meso-1,2-stilbenediol-1,2-dinitrate. This result indicated that the reaction was occurring by either retention or inversion of configuration at both asymmetric carbons. It was felt that retention at both sites was more reasonable, but the possibility of nitrate bridging was rejected in favor of phenyl participation. Although phenyl participation has been found for a number of systems (201, 202, 203, 204, 205, 206) the evidence for phenyl participation in 1,2-diarylethyl systems (207) indicates only limited involvement.

Although the possibility for phenyl participation in the stilbene oxidations with CAN exists, it is unlikely as the products formed if phenyl participation occurs would have the opposite stereochemistry as the observed products. That is, meso-1,2-stilbenediol-1,2-dinitrate would be generated from cis-stilbene while d,l-1,2-stilbenediol-1,2-dinitrate would be generated from trans-stilbene and the nitrate addition across the double bond would be forced to occur in a cis manner. The observed product stereochemistry could be accounted for by central carbon-carbon bond rotation before phenyl participation occurs, however, in this one would expect a similar distribution from the oxidation of both cis and trans-stilbene.

One, then is forced to account for the stereospecificity of product formation and bridging by nitrate appears to adequately account for the products formed. Whether the bridging occurs to form a bridged radical intermediate or a bridged cationic intermediate cannot be determined at this time.

Therefore, the oxidation of phenyl substituted olefins may be represented by Scheme 9.





Scheme 9. Proposed mechanism for the oxidation of phenyl substituted olefins by cerium(IV)

EXPERIMENTAL

Equipment

All equipment had previously been described on page 69.

Materials

Commercial Chemicals

Table 26 lists the chemicals obtained from commercial sources.

Table 26. Commercially obtained chemicals

Compound	Source
Ceric ammonium nitrate (CAN)	G. F. Smith Chemical Co.
Indene	Columbia
Styrene	Aldrich
trans-Stilbene	J. T. Baker
cis-Stilbene	Aldrich
trans-β-Methylstyrene	Aldrich
alpha-Pinene	Columbia
beta-Pinene	Aldrich
Norbornadiene	Aldrich
Norbornene	Aldrich
Methylenecyclohexane	Aldrich
1-Methylcyclohexene	Aldrich
Phenylacetylene	Aldrich
1-Octene	Aldrich
tert-Butylethylene	Aldrich
Cycloocta-1,5-diene	Columbia Carbon
Cycloocta-1,3-diene	Columbia Carbon

Prepared Compounds

Benzonorbornadiene The procedure of Friedman and Logullo (208) gave 12.2 g (20%) of benzonorbornadiene: nmr (CCl_4) δ 2.32 (m, 2H), 3.69 (m, 2H), 6.59 (m, 2H) and 6.90 (m, 4H).

trans-1,2-Dibromoindan Using the procedure of Winstein and Roberts (186) on 8.4 g of indene yielded 9.5 g (43%) of the indan: mp 30-2° (18 (186) 30-3°); nmr (CCl_4) δ 3.02 (dd ; J = 17 Hz, 1Hz; 1H), 3.62 (dd; J = 17 Hz, 5Hz; 1H), 4.70 (ddd; J = 5 Hz, 1 Hz, 1 Hz; 1H), 5.50 (d, J = 1 Hz, 1H) and 7.12 (m, 4H).

trans-1,2-Indandiol diacetate The procedure of Winstein and Roberts (186) was used on 9.5 g *trans*-1,2-dibromoindan to yield 7.3 g (93%) of the acetate: bp 150-2°/5 mm (lit (186) 134-6°/1.9 mm); nmr (CCl_4) δ 1.93 (s, 3H), 1.98 (s, 3H), 2.75 (dd; J = 16 Hz, 5 Hz; 1H), 3.42 (d,d; J = 16 Hz, 7 Hz; 1H), 5.33 (ddd; J = 7 Hz, 5 Hz, 4 Hz; 1H), 6.12 (d, J = 4 Hz, 1H) and 7.15 (m, 4H).

trans-1,2-Indandiol Using the procedure of Winstein and Roberts (186) on 7.3 g *trans*-1,2-indandiol diacetate yielded 2.0 g (33%) of the diol: mp 154-5° (lit (186) 156.5-157.5°); nmr (CD_3CN) δ 2.65 (dd; J = 16 Hz, 7 Hz; 1H), 2.85 (s, 2H), 3.16 (dd; J = 16 Hz, 7 Hz 1H), 4.29 (ddd; J = 5 Hz, 7 Hz, 7 Hz; 1H), 4.83 (d, J = 5 Hz, 1H) and 7.15 (m, 4H).

Oxidation of Olefins with CAN in Acetonitrile

Indene

To 1.0 g of indene in 10 ml of acetonitrile was added 9.5 g CAN in 20 ml of acetonitrile and the reaction was stirred at room temperature for 30 minutes. The reaction mixture was poured into 50 ml of water and extracted 3 times with 25 ml of pentane. The combined pentane extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 1 time with 25 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure to yield 1,2-indandiol-1,2-dinitrate: nmr (CCl_4) δ 2.98 (dd; J = 16.9 Hz, 3.8 Hz; 1H), 3.63 (dd; J = 16.9 Hz, 6.6 Hz; 1H), 5.62 (ddd; J = 6.6 Hz, 3.8 Hz, 2.8 Hz, 1H), 6.30 (d, J = 2.8 Hz, 1H) and 7.20 (m, 4H); ir (neat) cm^{-1} 2882 (w), 1626 (s) and 1269 (s); mass spectrum (70 eV) m/e (rel. intensity) 240 (30), 178 (24), 147 (92), 131 (46), 120 (100) and 119 (100); high resolution mass spectrum calc. for $C_9H_8N_2O_4$: 240.038229; observed: 240.038898; Anal. calc. for $C_9H_8N_2O_4$: C, 45.01; H, 3.33; N, 11.65. Found: C, 46.12; H, 3.49; N, 11.12.

Styrene

To 0.2 g styrene in 10 ml of acetonitrile was added 2.2 g of CAN in 15 ml of acetonitrile and the mixture was heated to reflux. After refluxing for 30 minutes, the reaction mixture was cooled and poured into 50 ml of water. The aqueous mixture was extracted 3 times with pentane. The combined pentane extracts were washed with 10 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 25 ml of water. The pentane solution was dried ($MgSO_4$) and the pentane was removed on a rotary evaporator at reduced pressure to yield 1,2-styrenediol-1,2-dinitrate: nmr (CCl_4) δ 4.63 (d, J = 6 Hz, 2H), 6.01 (t, J = 6 Hz, 1H), and 7.33 (m, 5H); ir (CCl_4) cm^{-1} 3080 (w), 3050 (w), 2980 (w), 2915 (w), 1670 (s), 1350 (m), 1295 (m), 915 (m) and 870 (s); Anal. calc. for $C_8H_8N_2O_4$: C, 42.11; H, 3.53; N, 12.28. Found: C, 42.29; H, 3.46, N, 12.08.

trans-β-Methylstyrene

To 1.3 g trans-β-methylstyrene in 40 ml acetonitrile was added 12 g CAN in 65 ml of acetonitrile and the mixture was stirred at room temperature for 45 minutes. The mixture was then flooded with 250 ml of water and extracted 3 times with 100 ml of pentane and 3 times with 100 ml of ether. The combined pentane extracts and the combined ether extracts were washed 3 times with 25 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 100 ml of water. The pentane solution and the ether solution were dried ($MgSO_4$).

The pentane was removed by rotary evaporation at reduced pressure to yield 1.4 g (58%) of 1,2-dihydroxy-*n*-propylbenzene-1,2-dinitrate: nmr (CCl_4) δ 1.33 (d, J = 6.5 Hz, 3H), 5.35 (qd; J = 6.5 Hz, 3.8 Hz; 1H), 6.00 (d, J = 3.8 Hz, 1H) and 7.35 (m, 5H); ir (CCl_4) cm^{-1} 3080 (w), 3040 (w), 3000 (w), 2920 (w), 1657 (s), 1285 (s), 1278 (s) and 853 (s); mass spectrum (70 eV) *m/e* (rel. intensity) 148 (7), 119 (36), 117)20), 106 (95), 105 (100) and 77 (100).

The ether was removed at reduced pressure on a rotary evaporator to yield 1.0 g (42%) of N-(nitrato-1-phenylpropyl)acetamide: nmr ($CDCl_3$) δ 1.21 (d, J = 6.5 Hz, 3H), 1.93 (s, 3H), 5.21 (m, 2H), 7.22 (m, 5H) and 8.25 (d broad, 1H); ir (CCl_4) cm^{-1} 3430 (m), 1695 (s), 1645 (s), 1270 (s) and 1085 (s).

trans-Stilbene

To 22 g of CAN in 100 ml of acetonitrile was added 3.6 g of trans-stilbene in 25 ml of acetonitrile and the reaction mixture was stirred at room temperature for 1 hour. The reaction mixture was poured into 250 ml of water, extracted 3 times with 25 ml of pentane and 3 times with

25 ml of ether. The combined pentane extractions and the combined ether extractions were washed 3 times with 25 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with saturated aqueous sodium chloride solution. The pentane solution and the ether solution were dried ($MgSO_4$).

The pentane was removed by rotary evaporation at reduced pressure to yield 2.9 g (48%) of meso-1,2-stilbenediol-1,2-dinitrate: mp 143-5° (lit (200) 148.5-149.5°); nmr ($CDCl_3$) δ 6.10 (s, 2H) and 7.31 (m, 5H); ir (CCl_4) cm^{-1} 1650 (s), 1540 (w), 1290 (s), 1275 (s) and 980 (s).

The ether was removed at reduced pressure by rotary evaporation to yield 2.8 g (46%) of a product tentatively identified as N-(2-nitrato-1,2-diphenylethyl)acetamide: mp 146-7°; nmr ($CDCl_3$) δ 1.88 (s), 1.95 (s), 5.52 (m), 6.15 (m), 7.20 (m), 7.97 (d) and 8.40 (d); ir (CCl_4) cm^{-1} 3460 (w), 3040 (w), 1690 (s), 1650 (s), 1510 (s) and 1285 (s); mass spectrum (70 eV) m/e (rel. intensity) 238 (7), 148 (79), 131 (36) and 106 (100).

cis-Stilbene

To 2.2 g of CAN in 20 ml of acetonitrile was added 0.36 g of cis-stilbene in 5 ml of acetonitrile and the reaction mixture was stirred at room temperature for 0.75 hours and poured into 50 ml of water. The aqueous mixture was extracted 3 times with 25 ml of pentane and 3 times with 25 ml of ether. The combined pentane extracts and the combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution, 3 times with 25 ml of water and 1 time with 25 ml of saturated aqueous sodium chloride solution.

The pentane was removed by rotary evaporation at reduced pressure to yield 0.25 g (41%) of d,l-1,2-stilbenediol-1,2-dinitrate: mp 102-4° (lit (200) 105.5-107.5°); nmr ($CDCl_3$) δ 6.10 (s, 2H) and 7.31 (m, 5H);

ir (CCl_4) cm^{-1} 3075 (w), 3020 (w), 2929 (w), 1658 (s), 1502 (w), 1460 (m), 1280 (s), 990 (m) and 855 (s).

The ether was removed at reduced pressure on a rotary evaporator to yield 0.30 g (50%) of a product tentatively identified as N-(2-nitrato-1,2-diphenylethyl)acetamide: nmr ($CDCl_3$) δ 1.85 (s), 1.92 (s), 5.46 (m), 6.01 (m) and 7.19 (m); ir (CCl_4) cm^{-1} 3460 (w), 3040 (w), 1690 (s), 1650 (s), 1510 (s) and 1285 (s); mass spectrum (70 eV) m/e (rel. intensity) 238 (6), 148 (56), 131 (65), 130 (20) and 106 (100).

Benzonorbornadiene

To 44 g of CAN in 100 ml of acetonitrile was added 2.06 g of benzonorbornadiene in 25 ml of acetonitrile and the mixture was stirred at room temperature for 1 hour. The mixture was then poured into 250 ml of water and extracted 3 times with 75 ml of pentane. The combined pentane extracts were washed 1 time with 100 ml of water. The pentane solution was dried ($MgSO_4$) and the pentane removed on a rotary evaporator at reduced pressure to give an oil which began crystallizing on standing. Recrystallization from pentane at low temperature yielded 3.1 g (62%) of exo-2-anti-7-dihydroxybenzonorbornene-2,7-dinitrate: mp 96-8°; nmr ($CDCl_3$) δ 2.19 (m, 2H), 3.56 (m, 1H), 3.89 (m, 1H), 4.91 (m, 2H) and 7.23 (m, 4H); ir ($CHCl_3$) cm^{-1} 1680 (s), 1270 (s) and 840 (s); mass spectrum (70 eV m/e (rel. intensity) 266 (2), 202 (22), 176 (57), 145 (94), 131 (100) and 117 (77); high resolution mass spectrum calc. for $C_{11}H_{10}N_2O_6$: 266.053878; observed: 266.052271; Anal. calc. for $C_{11}H_{10}N_2O_6$: C, 49.62; H, 3.76; N, 10.53. Found: C, 49.71; H, 3.87; N, 10.49.

Norbornadiene

To 4.82 g of CAN in 25 ml of acetonitrile was added 380 mg of norbornadiene and the reaction mixture was stirred at room temperature for 30 minutes. The mixture was poured into 50 ml of water and worked up with pentane as previously described to yield nitrate products: nmr (CCl_4) δ 1.80 (s), 1.92 (s), 2.47 (s, broad), 2.60 (s, broad), 4.98 (m), and 5.33 (m); ir (CCl_4) cm^{-1} 1655 (s), 1285 (s) and 860 (s).

Norbornene

To 5.48 g of CAN in 15 ml of acetonitrile was added 470 mg of norbornene in 10 ml of acetonitrile and the reaction mixture was heated to reflux for 1 hour. The mixture was cooled, poured into 50 ml of water and worked up with pentane as previously described to yield nitrate products: nmr (CCl_4) δ 1.6 (m, 6H), 2.8 (m, 2H) and 4.8 (m, 2H); ir (CCl_4) cm^{-1} 1665 (s), 1295 (s) and 870 (s).

alpha-Pinene

To 300 mg of *alpha*-pinene in 15 ml of acetonitrile was added 2.2 g of CAN in 15 ml of acetonitrile and the reaction mixture was stirred at room temperature for 15 minutes. The mixture was poured into 50 ml of water and worked up with pentane as previously described to yield nitrate products: nmr (CCl_4) δ 1.6 (m) and 5.1 (m); ir (neat) cm^{-1} 2940 (s), 1630 (s), 1280 (s) and 870 (s).

beta-Pinene

To 4.4 g of CAN in 20 ml of acetonitrile was added 500 mg of *beta*-pinene in 5 ml of acetonitrile and the mixture was stirred at room temperature for 30 minutes. The mixture was poured into 50 ml of water and worked up with pentane as previously described to yield nitrate products: ir (CCl_4) cm^{-1} 1630 (s), 1275 (s) and 870 (s).

Methylenecyclohexane

To 2.42 g of CAN in 20 ml of acetonitrile was added 200 mg of methylenecyclohexane in 5 ml of acetonitrile. The mixture was heated to reflux for 1 hour, cooled and poured into 50 ml of water. The mixture was worked up with pentane as previously described to yield nitrate products: ir (CCl_4) cm^{-1} 2950 (m), 1650 (s), 1645 (s), 1570 (m), 1280 (m) and 830 (s).

1-Methylcyclohexene

To 2.2 g of CAN in 20 ml of acetonitrile was added 200 mg of 1-methylcyclohexene and the mixture was heated to reflux for 1 hour. The mixture was cooled, poured into 50 ml of water and worked up with pentane as previously described to yield nitrate products: ir (CCl_4) cm^{-1} 2950 (m)-1642 (s), 1565 (m), 1290 (m), 1280 (s) and 825 (s).

Phenylacetylene

To 2.2 g of CAN in 15 ml of acetonitrile was added 0.21 g of phenylacetylene and the mixture was heated to reflux for 30 minutes. The mixture was cooled, poured into 50 ml of water and worked up with pentane as previously described to yield starting material: nmr (CCl_4) δ 2.92 (s, 1H) and 7.20 (m, 5H).

1-Octene

To 4.4 g CAN in 20 ml of acetonitrile was added 0.45 g of 1-octene in 5 ml of acetonitrile and the mixture was heated to reflux for 30 minutes. The mixture was cooled, poured into 50 ml of water and worked up as previously described to yield starting material: nmr (CCl_4) δ 1.1 (m), 2.0 (m), 4.3 (m), 4.95 (m) and 5.7 (m).

tert-Butylethylene

To 2.2 g of CAN in 20 ml of acetonitrile was added 0.16 g of tert-butylethylene in 5 ml of acetonitrile. The mixture was heated to reflux for 30 minutes, cooled and poured into 50 ml of water. The mixture was worked up with pentane as previously described to yield starting material: nmr (CCl_4) δ 0.97 (s, 9H), 4.70 (m, 2H) and 5.60 (m, 1H).

Cycloocta-1,5-diene

To 4.4 g of CAN in 50 ml of acetonitrile was added 0.2 g of cycloocta-1,5-diene and the mixture was stirred at room temperature for 30 minutes. The mixture was poured into 50 ml of water and worked up with pentane as previously described to yield starting material: nmr (CCl_4) δ2.39 (m, 8H) and 5.41 (m, 4H).

Cycloocta-1,3-diene

To 2.2 g of CAN in 15 ml of acetonitrile was added 0.22 g cycloocta-1,3-diene in 10 ml of acetonitrile. The color of the reaction mixture faded rapidly and the mixture was stirred for 15 minutes more. The mixture was poured into 50 ml of water and worked up with pentane as previously described to yield starting material: nmr (CCl_4) δ 1.90 (m, 8H) and 5.71 (m, 4H).

Cyclooctane

To 2.2 g of CAN in 30 ml of acetonitrile was added 0.22 g cyclooctane and the mixture was heated to reflux for 30 minutes. The mixture was cooled, poured into 50 ml of water and worked up with pentane as previously described to yield starting material: nmr (CCl_4) δ 1.40 (m), 2.08 (m) and 5.5 (m).

Absolute yields of dinitrate products in the oxidation of olefins by CAN

To 4.4 mmoles of CAN in 15 ml of acetonitrile was added 2.00 mmoles of substrate in 10 ml of acetonitrile. The mixture was stirred at room temperature or heated at reflux until the color of the solution had faded to pale yellow and precipitation of cerium(III) salts had ceased. The mixture was then poured into 50 ml of water and standard was added. The mixture was extracted 3 times with 25 ml of pentane. The combined pentane extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 1 time with 25 ml of water. The pentane solution was dried ($MgSO_4$) and the pentane was removed at reduced pressure on a rotary evaporator. The residue was dissolved in CCl_4 for nmr analysis. Extraction ration were determined by re-extraction techniques.

Table 27. Analysis of oxidation of olefins by CAN in acetonitrile to generate 1,2-dinitrates

Olefin	mmoles olefin	mmoles std.	area prod/H	area std/H	yield mmoles	yield %
Indene[a]	2.17	1.14	50.75	41.33	1.46	67.3
	2.18	1.23	53.50	43.68	1.56	71.6
	2.12	1.20	44.50	36.25	1.53	72.2
Styrene[b]	2.06	2.01	30.65	64.50	1.04	50.4
	2.03	1.49	33.50	53.40	1.02	50.5
	2.09	2.03	30.90	64.60	1.06	50.7
Stilbene[a] (trans)	2.00	1.33	38.10	43.70	1.16	58.0
	2.00	1.32	30.30	37.25	1.08	54.0
	2.00	1.25	37.80	43.50	1.09	54.5

[a] Dibenzylether used as standard.

[b] *p*-Chlorotoluene used as standard.

Oxidation of Olefins with CAN in 50% Aqueous Acetonitrile

Indene

To 0.45 g of indene in 20 ml of 50% aqueous acetonitrile was added 4.4 g of CAN in 10 ml of 50% aqueous acetonitrile. The mixture was stirred at room temperature for 15 minutes and poured into 50 ml of water. The mixture was extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 1 time with 25 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed at reduced pressure on a rotary evaporator to yield a viscous oil which when trituated with pentane yielded 250 mg (35%) of 1,2-indandiol-2-nitrate: mp 128-30^o; nmr (CD_3CN) 100 MHz δ 3.08 (dd; J = 16 Hz, 4 Hz, 1H), 3.30 (dd; J = 16 Hz, 6 Hz, 1H); 3.70 (d, J = 7 Hz, 1H), 5.30 (dd; J = 7 Hz, 8 Hz; 1H), 5.67 (dd; J = 6 Hz, 8 Hz; 1H) and 7.30 (m, 4H); ir ($CHCl_3$) cm^{-1} 3600 (w), 1645 (s), 1290 (m) and 870 (m); mass spectrum (70 eV) <u>m/e</u> (rel. intensity) 195 (33), 148 (55), 131 (73), 119 (45), 103 (100) and 91 (93); high resolution mass spectrum calc. for $C_9H_9NO_4$: 195.053151; observed 195.051289; <u>Anal</u>. calc. for $C_9H_9NO_4$: C,55.38; H, 4.61; N,7.18 . Found: C,56.57; H,4.79 ; N,6.75.

Styrene

To 400 mg of styrene in 10 ml of 50% aqueous acetonitrile was added 4.4 g of CAN in 15 ml 50% aqueous acetonitrile and the mixture was heated to reflux for 15 minutes. The mixture was cooled, poured into 50 ml of water and extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 1 time with 25 ml of water. The ether solution was dried

($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure. The residue was dissolved in carbon tetrachloride and analyzed by nmr. The reaction yielded a mixture of 1,2-styrenediol-1,2-dinitrate and benzaldehyde.

Reduction of 1,2-indandiol-1,2-dinitrate with hydrogen over palladium

The product from the oxidation of 180 mg of indene with CAN in acetonitrile was taken up in 7 ml of 95% aqueous ethanol and added to 20 mg of 10% palladium on charcoal. The mixture was subjected to hydrogenation at 1 atmosphere for 16 hours. After 4 hours, 54 ml of hydrogen had been taken up and 3 ml more were taken up in the next 12 hours. The palladium was filtered and the filtrate was added to 100 ml of water and extracted 3 times with 25 ml of ether. The ether solution was dried ($MgSO_4$) and the ether was removed at reduced pressure on a rotary evaporator to yield 150 mg (67% from indene) of trans-1,2-indandiol: mp 154-5° (lit (185) 156.5-7.5°); mixed mp 154-5°; nmr (CD_3CN)δ2.65 (dd; J = 16 Hzm, 7 Hz; 1H), 2.85 (s, 2H), 3.16 (dd; J = 16 Hz, 7 Hz; 1H), 4.29 (ddd; J = 5 Hz, 7 Hz, 7 Hz; 1H), 4.83 (d, J = 5 Hz, 1H) and 7.15 (m, 4H).

Reduction of 1,2-indandiol-1,2-dinitrate with zinc and acetic acid

Product from the oxidation of 5.4 g of indene was dissolved in 50 ml of acetic acid which was added to 45.5 g of zinc in 85 ml of water with stirring. The temperature of the reaction mixture was maintained at 10-20° during the addition and for 1 hour afterwards. The reaction mixture was warmed to 80°, filtered and the zinc washed with 5% aqueous hydrochloric acid. The precipitate which had formed was dissolved in 30% aqueous sodium hydroxide solution and the resulting alkaline solution was extracted 4 times with 100 ml of ether. The ether was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure to yield 300 mg (5%) of trans-1,2-indandiol: mp 154-5° (lit (185) 156.5-7.5°).

Reduction of 1,2-indandiol-1,2-dinitrate with hydrazine and palladium

The product from the oxidation of 1.0 g of indene with CAN in acetonitrile was dissolved in 50 ml of methanol and added to 1.0 g of 10% palladium on charcoal in a 3-neck round-bottomed flask flushed with nitrogen. To this was added 15 ml of 95% hydrazine hydrate in 25 ml of methanol. The mixture was stirred for 1 hour, filtered and the solvent removed under reduced pressure on a rotary evaporator. The residue was added to 50 ml of water and extracted 3 times with 25 ml of ether. The combined ether extracts were dried ($MgSO_4$) and the ether removed by rotary evaporation at reduced pressure yielding 100 mg (8%) of trans-1,2-indandiol: mp 153-4° (lit (185) 156.5-7.5°); mixed mp 153-4°.

Reduction of exo-2-anti-7-dihydroxybenzonorbornene

To 1.2 g of lithium aluminum hydride in 50 ml of ether was added 1.0 g of 2,7-dihydroxybenzonorbornene-1,2-dinitrate in 25 ml of ether at a rate that the ether gently refluxed. The reaction mixture was stirred for 1 hour after the addition was completed and the excess LAH was decomposed with 9% aqueous HCl solution. The aqueous layer was continuously extracted with ether for 12 hours. The ether solution was dried ($MgSO_4$) and the ether was removed at reduced pressure on a rotary evaporator to yield 500 mg (75%) of 2,7-dihydroxybenzonorbornene: nmr ($CDCl_3$)δ2.00 (m, 2H), 3.30 (m, 2H), 3.62 (s, 2H), 4.03 (m, 2H) and 7.12 (m, 4H); ir (CCl_4) cm^{-1} 3350 (s, broad), 2980 (s), 2950 (s), 1560 (s), 1472 (s), 1422 (s), 1180 (s) and 1065 (s); mass spectrum (70 eV) m/e (rel. intensity) 176 (5), 158 (100), 130 (84), 129 (100) and 116 (100).

Acetolysis of 2,7-dihydroxybenzonorbornene

To 150 mg of 2,7-dihydroxybenzonorbornene in 5 ml of acetic anhydride was added 1 drop of concentrated sulfuric acid and the mixture was heated to reflux for 15 minutes. The mixture was cooled, poured into 25 ml of water and extracted 3 times with 10 ml of ether. The combined ether extracts were washed with 1.2 N aqueous sodium hydroxide solution until neutral and 1 time with 10 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed at reduced pressure on a rotary evaporator to yield 160 mg (80%) of 2,7-dihydroxybenzonorbornene-2,7-diacetate: nmr (CCl_4) δ 2.00 (m, 8H), 3.33 (m, 1H), 3.62 (m, 1H), 4.57 (m, 2H) and 7.09 (m, 4H); ir (CCl_4) cm^{-1} 2990 (w), 2960 (w), 1745 (s), 1260 (s), 1240 (s) and 1060 (s); mass spectrum (70 eV) m/e (rel. intensity) 201 (37), 141 (35), 129 (100) and 116 (46).

Acetonide of 2,7-dihydroxybenzonorbornene

Used a modification of the procedure of Zedoric and coworkers (209). To 150 mg of 2,7-dihydroxybenzonorbornene in 40 ml of acetone was added 0.5 ml of 70% perchloric acid and the mixture was stirred at room temperature for 2 hours. The mixture was poured into 100 ml of water and extracted 3 times with 25 ml of pentane and 3 times with 25 ml of ether. The ether solution was dried ($MgSO_4$) and the ether was removed by rotary evaporation at reduced pressure to yield 103 mg of 2,7-dihydroxybenzonorbornene acetonide: nmr (CCl_4) δ 1.23 (s, 6H), 1.90 (m, 2H), 2.53 (s, 2H), 3.20 (m, 2H) and 7.00 (m, 4H); mass spectrum (70 eV) m/e (rel. intensity) 216 (21), 180 (16), 158 (63), 145 (100) and 130 (59).

PART IV

REACTIONS OF CERIC AMMONIUM NITRATE WITH SUBSTITUTED BIBENZYLS

SUMMARY OF PART IV

The oxidation of 1,2-diarylethanes by ceric ammonium nitrate (CAN) in 70% aqueous acetonitrile (0.36 N HNO_3) at 80° was found to generate cleavage products: substituted benzaldehydes, substituted benzyl nitrates and substituted benzyl alcohols.

The mechanism of the oxidation was studied by competitive oxidation of a series of 1,2-diarylethanes with CAN and subjecting the relative rate data to a Hammett correlation. Other competitive oxidation of 2,3-diphenyl-2,3-dimethylbutane with 1,2-diphenylethane was also performed.

A mechanism for the oxidation has been postulated involving electron abstraction from the π-system as the rate determining step. A cleavage process then occurs to generate a benzyl radical and benzyl cation in a single step. These cleavage species then lead to the observed products. This is the first analogy with mass spectral processes observed for a metal ion oxidation in solution.

HISTORICAL

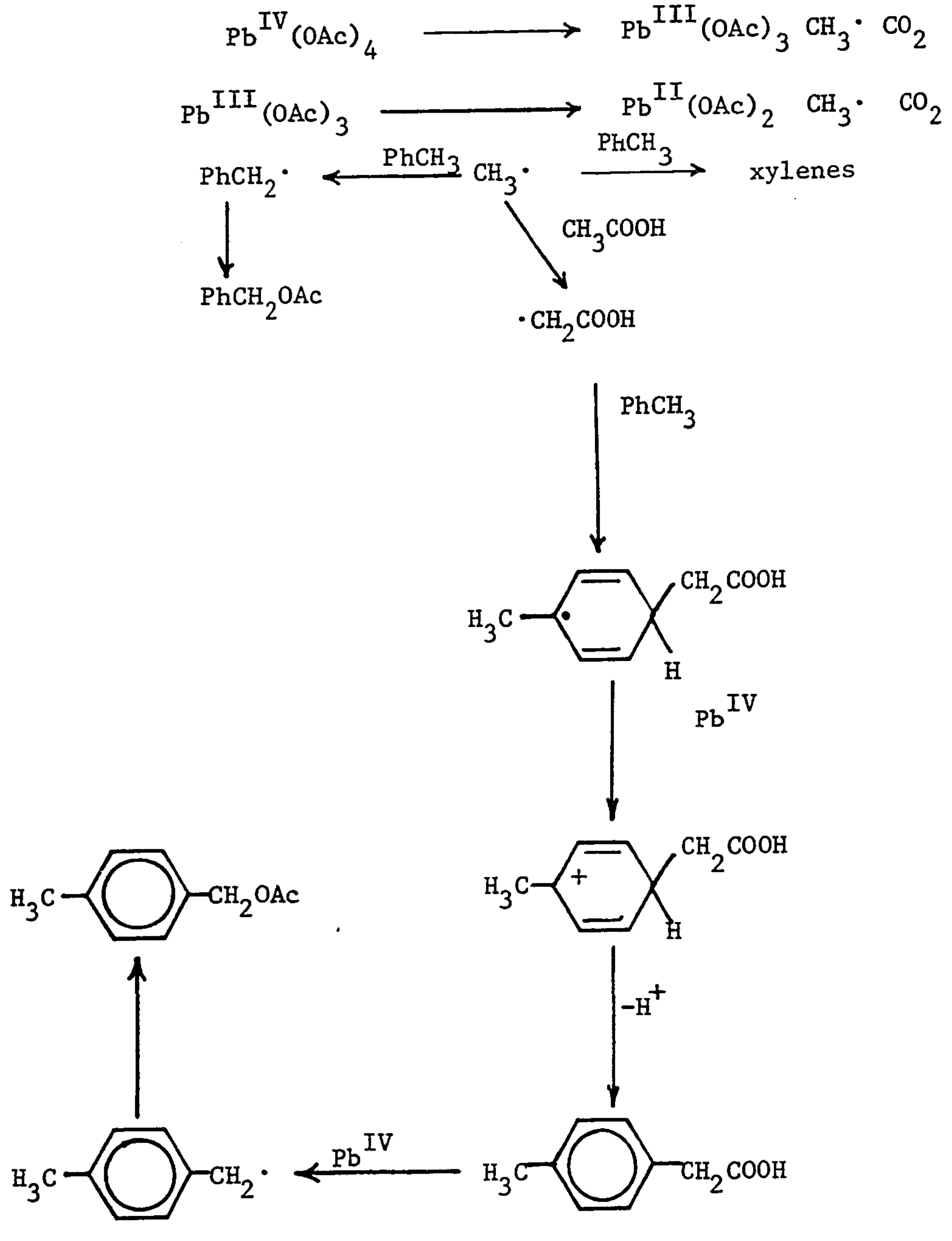
Lead Tetraacetate (LTA)

The oxidation of toluene by LTA to give an 11% yield of benzyl acetate was first observed by Dimroth and Schweizer (210). The reaction was later extended to ethylbenzene to yield 32-4% of 1-phenylethanol acetate (211), diphenylmethane to give 71% of benzhydryl acetate (210, 211) and triphenylmethane to give 50% of triphenylmethyl acetate (210, 211).

When Fieser and coworkers (212) oxidized 2,4,6-trinitrotoluene with LTA, the expected benzyl acetate was not produced by instead a fair yield of 2,4,6-trinitro-1,3-dimethylbenzene was isolated. When chlorobenzene was used as substrate, the products isolated were chlorobenzyl acetates. In the oxidation of benzene, Fieser and coworkers isolated only benzyl acetate.

Later, Davies (213) re-examined the oxidation of chlorobenzene with LTA and postulated a mechanism involving free radical methylation of chlorobenzene to give chlorotoluenes which are further oxidized to chlorobenzyl acetates. The oxidation of the toluenes to the acetates is envisioned as proceeding through a lead intermediate, as no bibenzyls are found, rather than a free radical process.

Recently, the oxidation of toluene with LTA was studied by Heiba and coworkers (214). In the oxidation, the major products isolated were benzyl acetate and methylbenzyl acetates along with minor amounts of xylenes and methylphenylacetic acids. It was found that oxygen inhibits the reaction and the products based on LTA consumed are decreased. The following mechanism was postulated.


Pb^IV(OAc)_4
Pb^III(OAc)_3 CH_3· CO_2
Pb^III(OAc)_3
Pb^II(OAc)_2 CH_3· CO_2
PhCH_2·
PhCH_3
CH_3·
PhCH_3
xylenes
CH_3COOH
PhCH_2OAc
·CH_2COOH
PhCH_3
H_3C
CH_2COOH
H
Pb^IV
H_3C
+
CH_2COOH
H
-H^+
H_3C
CH_2OAc
H_3C
CH_2·
Pb^IV
H_3C
CH_2COOH

Manganese

The oxidation of bibenzyl and triphenyl methane with manganese(III) acetate was reported by Zonis (215). It was also found that 1,1,1-triphenylmethane, cyclohexene and stilbene were not oxidized under similar conditions. Later, Venkatachalapathy and coworkers (216) oxidized toluene with manganese(III) sulfate to yield benzaldehyde and benzyl alcohol.

A number of workers (217, 218, 219) have oxidized a series of substituted aromatic compounds with manganese(III) acetate in acetic acid. In the oxidation of p-methoxytoluene with product isolated was p-methoxybenzyl acetate and in the oxidation of 1-methoxynaphthalene the product was 4-methoxy-1-naphthyl acetate and for 2-methoxynaphthalene, the product was 2-methoxy-1,4-naphthoquinone. In all oxidations, the postulated mechanism involves formation of a radical cation by electron

$$\mathrm{ArCH_3} + \mathrm{Mn(III)} \rightleftharpoons (\mathrm{ArCH_3})^{+\cdot} + \mathrm{Mn(II)}$$

$$(\mathrm{ArCH_3})^{+\cdot} \longrightarrow \mathrm{ArCH_2}\cdot + \mathrm{H}$$

$$\mathrm{ArCH_2}\cdot + \mathrm{Mn(III)} \longrightarrow \mathrm{ArCH_2}^{+} + \mathrm{Mn(II)}$$

$$\mathrm{ArCH_2} + \mathrm{HOAc} \longrightarrow \mathrm{ArCH_2OAc} + \mathrm{H}$$

transfer from the aromatic nucleus, followed by proton loss in the rate determining step to yield a radical species which is further oxidized by manganese(III) to the cation which leads to products.

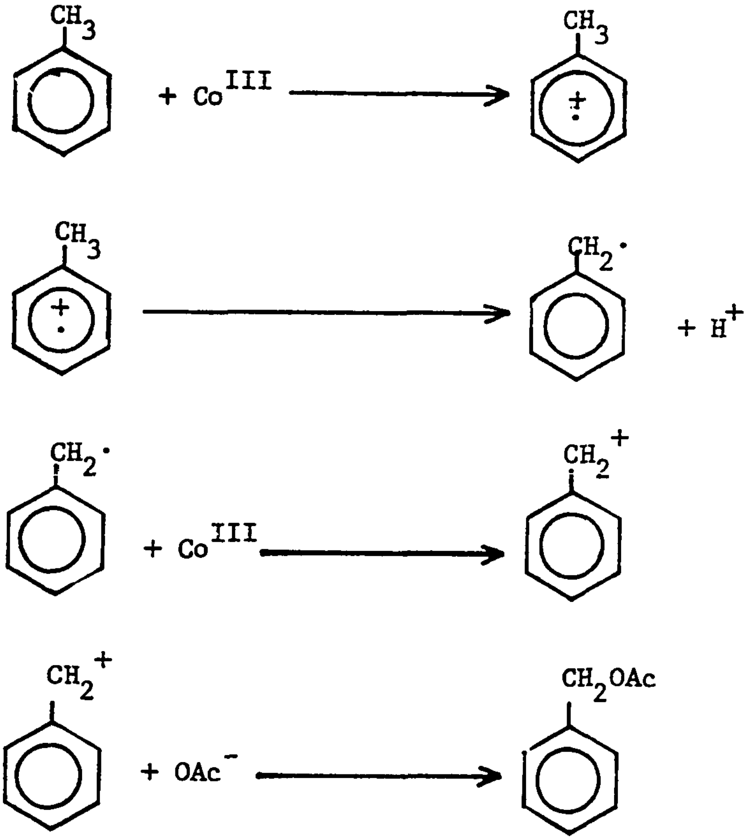
Later, the oxidation of toluenes by manganese(III) acetate in acetic acid was examined by Heiba and coworkers (126). Two competing mechanisms were postulated for the reaction, one a free radical mechanism resulting from the reaction of the toluene with a carboxymethyl radical generated by the thermolysis of the manganese(III) acetate. The second mechanism is an electron transfer mechanism to form a radical cation and is important in the oxidation of aromatic hydrocarbons having an ionization potential of ≤ 8 eV.

Cobalt

The oxidation of aromatic hydrocarbons by cobalt(III) was first studied by Cooper and coworkers (220, 221). They found the reaction to be second order overall and first order in substrate and oxidant. From the reactivity of a series of aromatic hydrocarbons, an outer sphere mechanism is postulated. The oxidation may proceed through an electron transfer mechanism involving abstraction of a π-electron or by hydrogen atom abstraction on the side chain of arylalkyl hydrocarbons.

Sakota and coworkers (222) made a detailed kinetic study of the oxidation of toluenes with cobalt(III) acetate in aqueous acetic acid. The activation energies for toluene, ethylbenzene, cumene, diphenyl methane and triphenyl methane were found to be the same. The oxidation was postulated as proceeding <u>via</u> an initial reversible electron transfer from toluene to generate the radical cation of toluene which is further oxidized to benzyl acetate by cobalt(III).

The cobalt(III) acetate oxidation of alkyl aromatic hydrocarbons was studied by Heiba and coworkers (124). A mechanism was postulated involving electron transfer to generate radical cations by abstraction of an electron from the π-system. A Hammett correlation was found with $\rho = -2.4$, however, addition of chloride ion decreased the ρ to -1.35.



This was attributed to the formation of a cobalt complex of high oxidation potential and lower selectivity. Evidence for the formation of radical cations was obtained by observation of the esr signal for the radical cations of *p*-methoxytoluene, hexamethylbenzene, pentamethylbenzene and durene. Later, Dessau and coworkers (125) also observed the esr signal for the radical cations of 1,3,5-tri-*t*-butylbenzene and 1,4-di-*t*-butylbenzene generated by cobalt(III) acetate in trifluoroacetic acid using a flow system.

Chester (223, 224) used potassium 12-tungstocobaltate(III) to oxidize a series of arylalkyl hydrocarbons to determine whether inner or outer sphere electron transfer occurs in the formation of aromatic radical cations. The oxidation products from the oxidation of toluene and *o*-, *m*- and *p*-xylenes were diphenylmethane derivatives. The oxidation is postulated as proceeding *via* an outer sphere oxidation in which the electron is removed from the aromatic π system. The radical cation then expels a proton and the resulting benzyl radical is oxidized to the cation which gives the observed products.

Chromium

The oxidation of arylalkyl hydrocarbons by chromium(VI) compounds can selectively convert side chains to a series of different products. Chromic acid has been found to oxidize phenylalkanes to benzoic acids (225, 226) while dichromate oxidizes arylalkanes to the corresponding carboxylic acid or ketone (227, 228). Chromyl chloride has been found to yield substituted benzaldehydes from toluenes and β-phenylcarbonyl products from arylalkanes (229, 230). Chromyl acetate oxidizes toluenes to the corresponding benzaldiacetates (231, 232). The oxidation of toluene to benzyl alcohol by bis(trimethylsilyl)chromate has also been reported (233).

The kinetics of the oxidation of diphenylmethane with chromic acid were extensively studied by Wiberg and Evans (234). It was found that the rate was first order in diphenylmethane, oxidant and the Hammett acidity function. A kinetic isotope effect $k_H/k_D = 6.4$ was found and a Hammett correlation with $\rho = -1.17$ was found. These results were taken to suggest that the reaction proceeds through hydrogen atom abstraction to form a benzhydryl radical. The benzhydryl radical is then further oxidized to give the observed product, benzophenone.

The kinetics of the oxidation of substituted toluenes have been examined by Stairs (235) and Duffin and Tucker (236). A mechanism is postulated by Stairs involving an initial equilibrium between free oxidant and substrate and a π complex. The complex decomposes in the rate determining step to yield a benzylchromate ester which leads to products.

Cerium

Cerium(IV) has been known to oxidize toluenes to benzaldehydes for a number of years (237, 238), however the oxidative conditions are somewhat severe.

Ramaswamy and coworkers (239) reported the oxidation of p-xylene to p-tolualdehyde with electrochemically generated cerium(IV) sulfate in aqueous sulfuric acid. The authors postulate a series of one electron oxidations for the mechanism of the oxidation.

Syper (240) has reported the oxidation of substituted toluenes by ceric ammonium nitrate (CAN) to the corresponding benzaldehyde in high yield employing dilute nitric acid as solvent. Dust and Gill (241) attempted to oxidize o-xylene to o-tolualdehyde by Syper's method and isolated o-methylbenzyl nitrate rather than the aldehyde. The authors find that aldehyde formation is dependent upon hydrolysis of the nitrate to the corresponding alcohol which is rapidly oxidized to the aldehyde. Trahanovsky and Peters (242) have also found evidence supporting the intermediacy of nitrates in the reaction.

Trahanovsky and Young (243) have oxidized a series of substituted toluenes in 50% aqueous acetic acid to yield the corresponding benzaldehyde or in glacial acetic acid to yield the corresponding benzyl acetate. Mechanistic possibilities included either two one-electron oxidations or one two-electron oxidation. Young (244) later studied the mechanism of the oxidation of substituted toluenes with CAN in glacial acetic acid at 100-110°. A Hammett treatment of the kinetic data indicated free radical character for the reaction if electron withdrawing substituents were present and carbenium ion character if the substituents were electron donating. A kinetic isotope effect of $k_H/k_D \approx 1.8$ was found for the oxidation of toluene and toluene-$\alpha,\alpha,\alpha,$-d_3 at 100-110°.

Electrolytic

The anodic oxidation of toluene in acetonitrile has been studied by Eberson and Olofsson (245) where products derived radical intermediates and cationic intermediates were observed. The postulated mechanism for the oxidation involves hydrogen abstraction from the π-system in the initial step. The radical cation then loses a proton to generate a benzyl radical which is further oxidized to the cation.

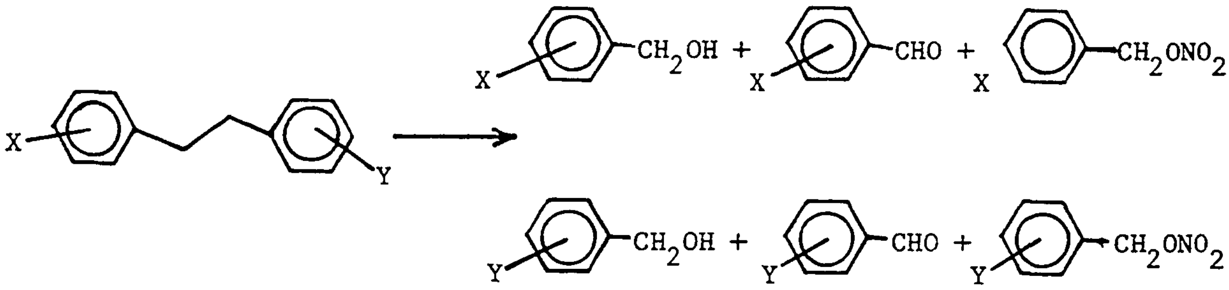
Nyberg (246) has found the anodic oxidation of mesitylene yields bimesityl as the major product. The mechanism is thought to involve formation of a mesitylene radical cation in the initial oxidation step.

Reviews

A good review of the oxidation of hydrocarbons by transition metal oxidants has been written by Lee (247).

RESULTS

The oxidation of 1,2-diarylethanes with ceric ammonium nitrate (CAN) in 70% aqueous acetonitrile (0.36 N HNO_3) yielded substituted benzaldehydes, substituted benzyl alcohols and substituted benzyl nitrates. The results



from the oxidation of a series of 1,2-diarylethanes are presented in Table 28.

Table 28. Absolute yields of products in the oxidation of 1,2-diarylethanes by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

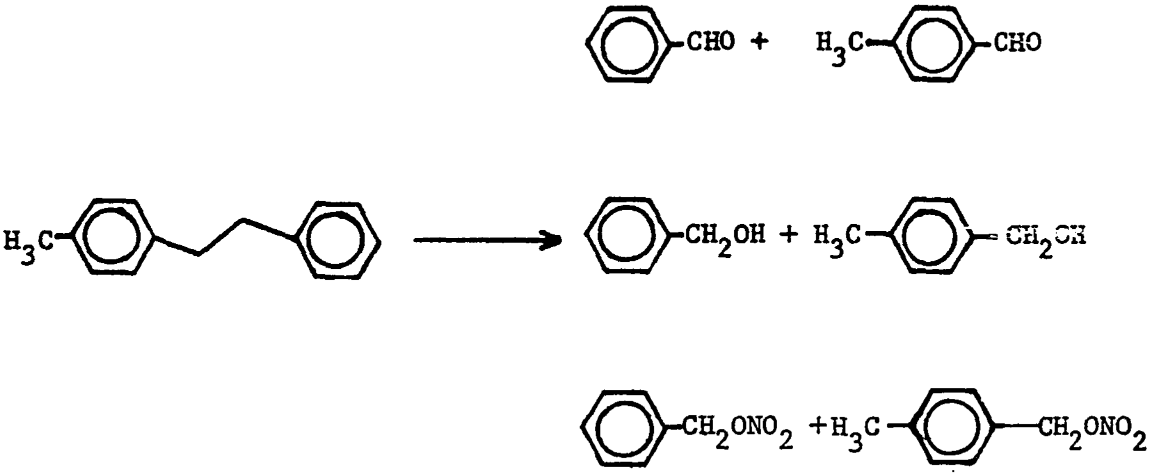
1,2-Diarylethane (mmoles)	CAN (mmoles)	Yield (mmoles)[a,b,c]		
		ArCHO	$ArCH_2OH$	$ArCH_2ONO_2$
$(C_6H_5CH_2)_2$ (2.2)	8.0	1.36 ±0.07	0.08 ±0.03	0.88 ±0.66
$(\underline{p}\text{-}CH_3OC_6H_5CH_2)_2$ (2.1)	8.0	2.45 ±0.02	0.50 ±0.01	0.03 ±0.01
$(\underline{p}\text{-}CH_3C_6H_5CH_2)_2$ (1.9)	10.0	1.91 ±0.03	0.44 ±0.02	0.23 ±0.02

[a] All yields are determined by nmr on unpurified products.

[b] Diphenylmethane was used as standard in all cases.

[c] All yields based on at least 2 runs.

The oxidation of the unsymmetrical 1,2-diarylethane, 1-p-tolyl-2-phenylethane, with CAN was also performed in 70% aqueous acetonitrile (0.36 N HNO_3). The products observed were benzaldehyde (0.39 mmoles), p-tolualdehyde (1.26 mmoles), benzyl alcohol (0.14 mmoles), p-methylbenzyl alcohol (0.09 mmoles), benzyl nitrate (0.85 mmoles) and p-methylbenzyl nitrate (0.21 mmoles). The reaction was run using 2.00 mmoles of 1-p-tolyl-2-phenylethane and 10.0 mmoles of CAN.



A competitive oxidation of 2,3-diphenyl-2,3-dimethylbutane and 1,2-diphenylethane with CAN was run in 70% aqueous acetonitrile (0.36 N HNO_3). The CAN used was insufficient to oxidize the starting materials completely and the amounts of starting materials remaining were determined by nmr analysis with diphenylmethane as internal standard.

Table 29. Relative rate of oxidation of 2,3-diphenyl-2,3-dimethylbutane (bicumyl) <u>versus</u> 1,2-diphenylethane (bibenzyl) with CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

Run[a]	mmoles standard	mmoles bicumyl	mmoles bibenzyl	k_{BC}/k_{BB}
1	1.83	1.47	1.87	4.60
2	1.99	1.37	1.87	5.65
3	1.96	1.33	1.87	6.10

[a] 2.00 mmoles each of bicumyl and bibenzyl initially.

The relative rates of the CAN oxidation of a series of 1,2-diarylethanes in 70% aqueous acetonitrile (0.36 N HNO_3) were obtained. A Hammett correlation was found when the log of the relative rates were plotted against σ values. The relative rate data are presented in Table 30 , while the σ values are presented in Tables 2 and 18, except for the

Table 30. Relative rates of the oxidation of 1,2-diarylethanes by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

Substituents	k/k_H	log (k/k_H)
p-CH_3,p-CH_3	65.32 ± 1.93	1.816
p-CH_3,H	29.03 ± 0.68	1.750
H,H	1.00	0.000
p-Cl,p-Cl	0.291 ± 0.04	-0.538
m-Cl, M-Cl	0.0408 ± 0.007	-1.359

(σ^+ + σ^+) value for the 1,2-di-p-chlorophenylethane which is 0.798.

The Hammett $\rho\sigma$ plots are shown in Figures 4, 5, 6, 7 and the ρ values from the plots are presented in Table 31.

Table 31. Values for ρ obtained from Hammett $\rho\sigma$ plots.

σ Values	ρ Value
σ^+	-5.54 ± 0.17^a
σ^+	-4.61 ± 0.43
$\sigma^+ + \sigma^+$	-2.98 ± 0.50^a
$\sigma^+ + \sigma^+$	-2.41 ± 0.34

[a] Point for log ($k_{m\text{-}Cl}/k_H$) was not used in plot.

Figure 4. Hammett plot (σ^+) for the oxidation of 1,2-diarylethanes by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

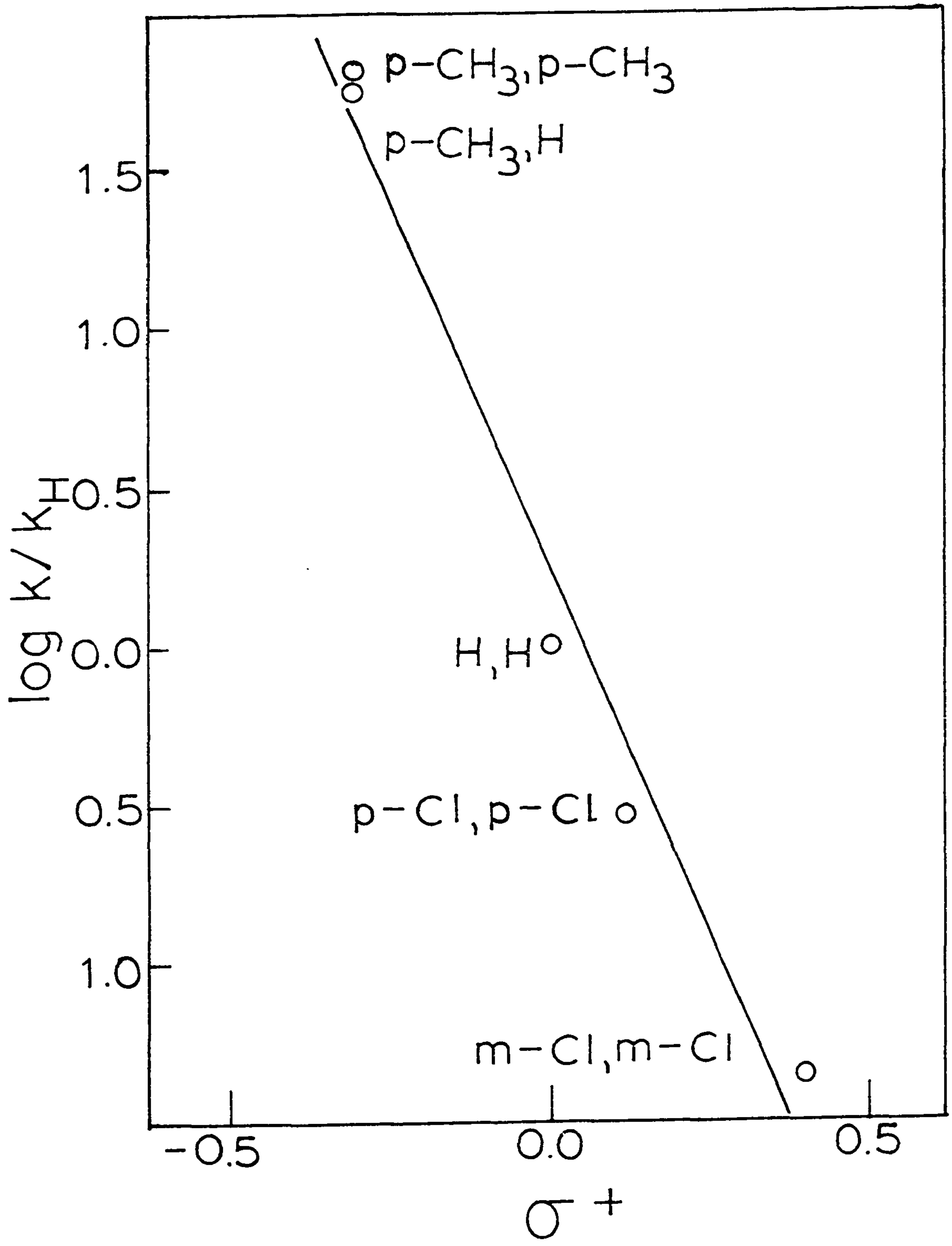

log k/k$_H$
1.5
1.0
0.5
0.0
0.5
1.0
-0.5
0.0
0.5
σ^+
p-CH$_3$,p-CH$_3$
p-CH$_3$,H
H,H
p-Cl,p-Cl
m-Cl,m-Cl

Figure 5. Hammett plot ($\sigma^+ + \sigma^+$) for the oxidation of 1,2-diarylethanes by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

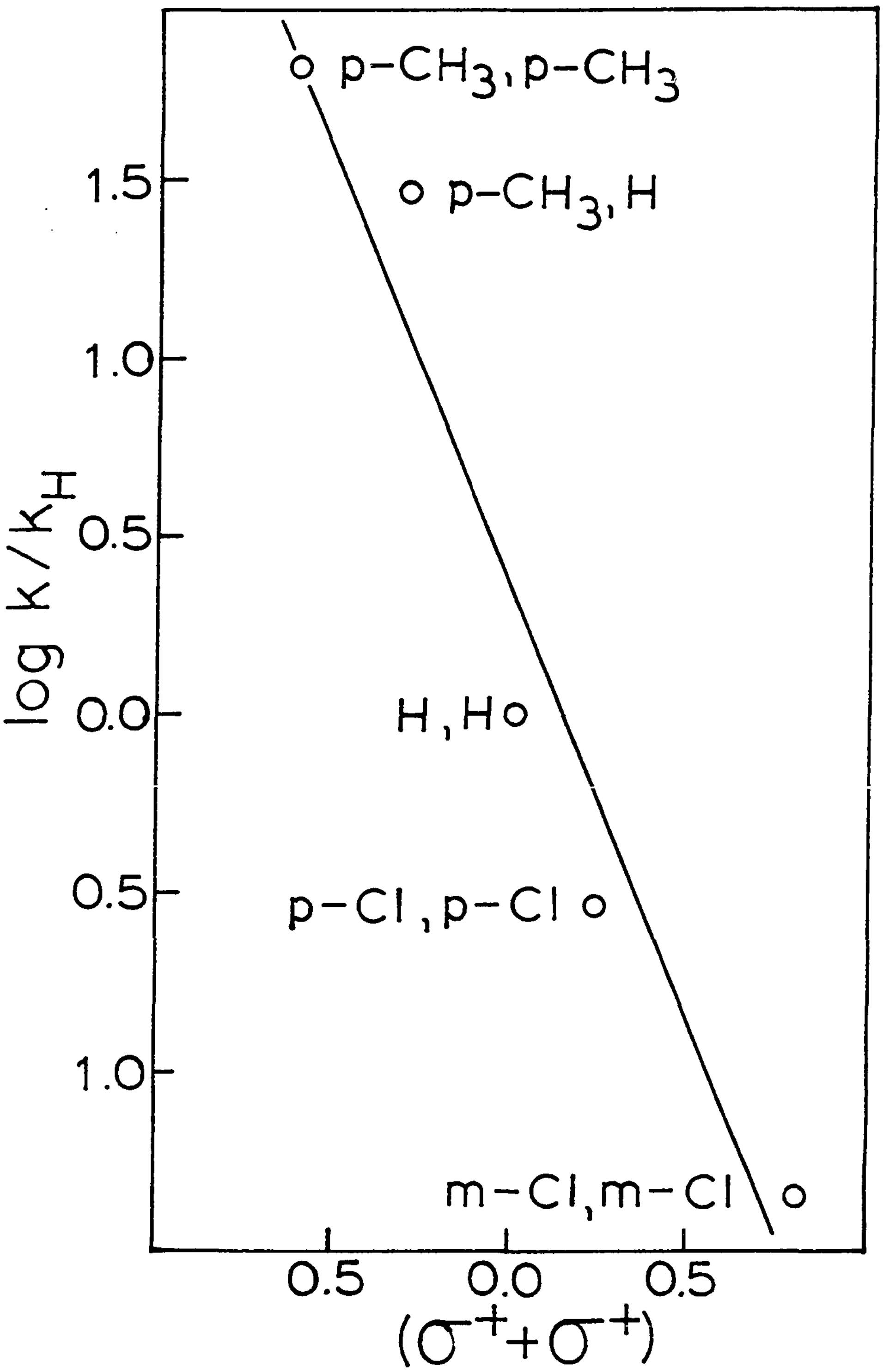

log k/k_H
1.5
1.0
0.5
0.0
0.5
1.0
0.5
0.0
0.5
(σ⁺+σ⁺)
p-CH3,p-CH3
p-CH3,H
H,H
p-Cl,p-Cl
m-Cl,m-Cl

Figure 6. Hammett plot (σ^+) for the oxidation of 1,2-diarylethanes in 70% aqueous acetonitrile (0.36 N HNO_3) by CAN at 80° (k_{m-Cl}/k_H not included)

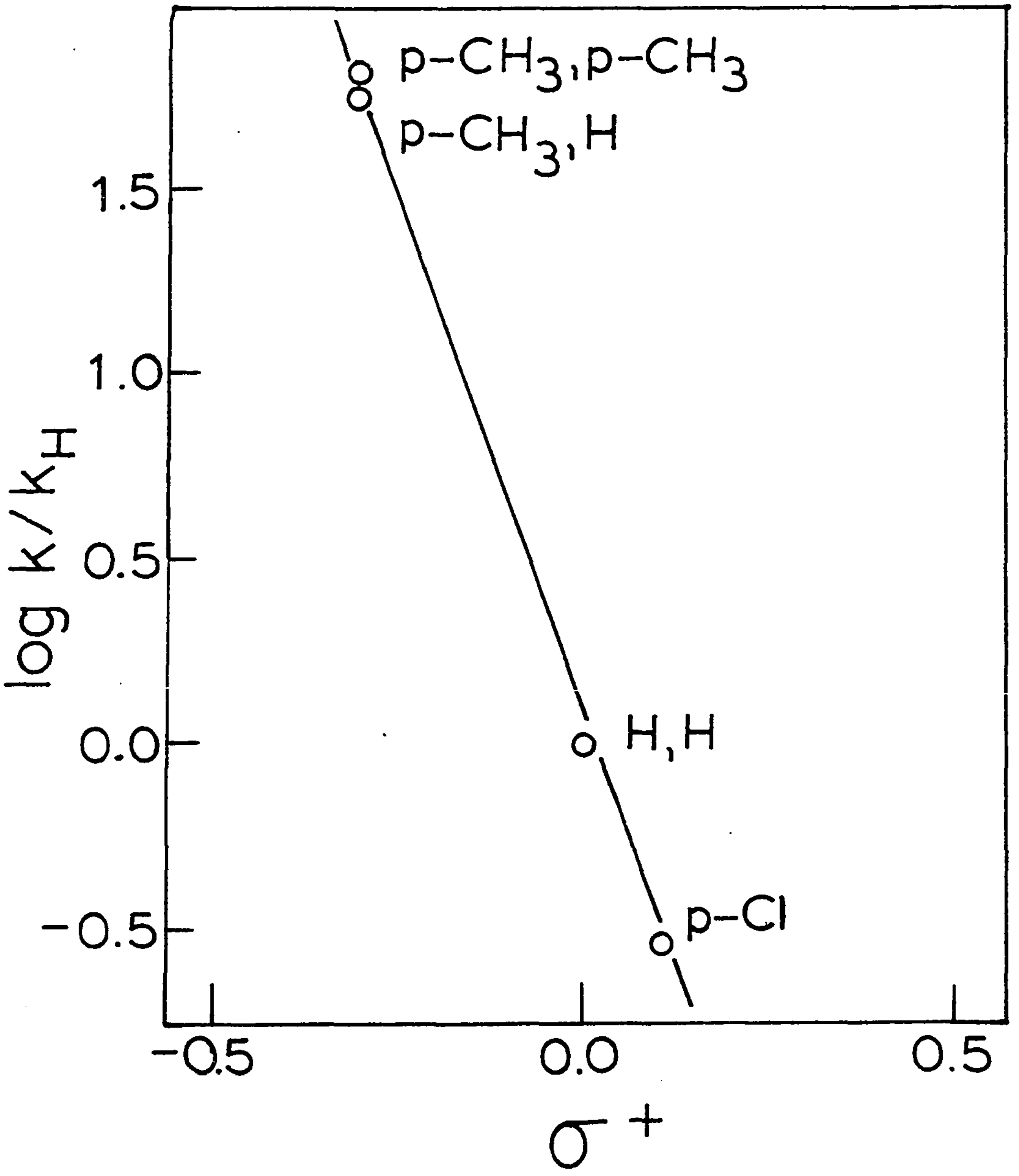
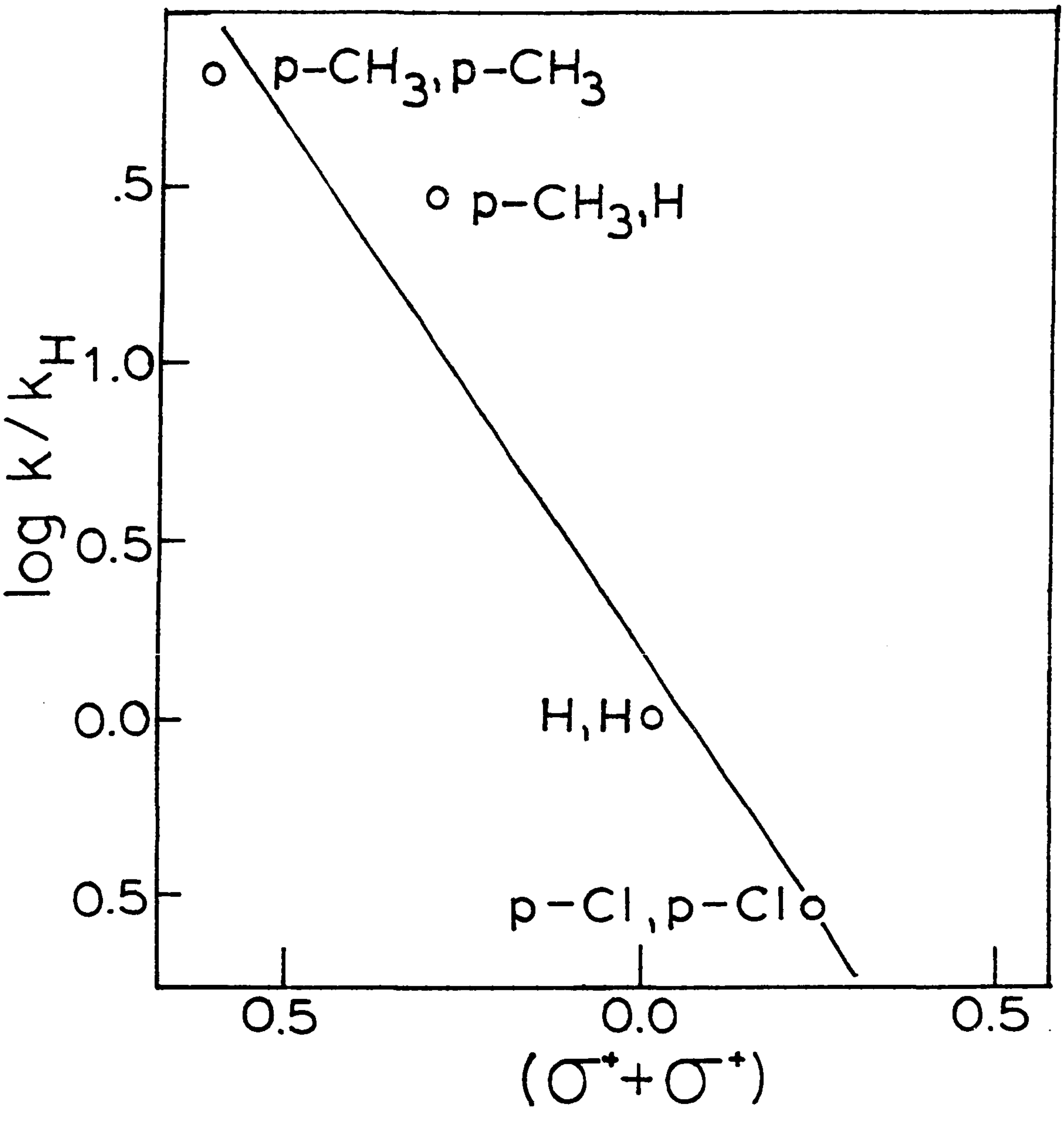

p-CH$_3$,p-CH$_3$
p-CH$_3$,H
H,H
p-Cl
1.5
1.0
0.5
0.0
−0.5
log k/k$_H$
−0.5
0.0
0.5
σ$^+$

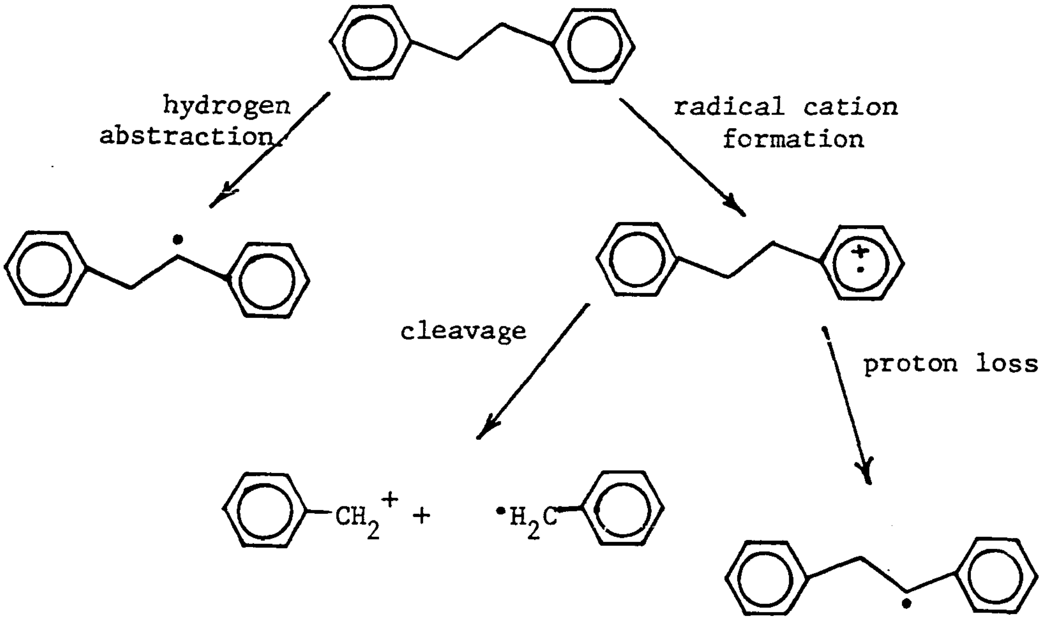
Figure 7. Hammett plot ($\sigma^{+}+\sigma^{+}$) for the oxidation of 1,2-diarylethanes in 70% aqueous acetonitrile (0.36 N HNO_3) by CAN at 80^{o} (k_{m-Cl}/kH not included)


p-CH3,p-CH3
p-CH3,H
H,H
p-Cl,p-Cl
log k/kH
.5
1.0
0.5
0.0
0.5
0.5
0.0
0.5
(σ+ + σ+)

DISCUSSION

In the previous work involving the oxidation of aryl alkyl hydrocarbons by cerium(IV) the postulated mechanism for the oxidation has involved the abstraction of α-hydrogen atoms from the benzlic position on the side chain to generate benzyl radicals (239, 240, 243). Recently however, many workers (124, 126, 206, 207, 208) are considering the possibility of mechanisms involving radical cations formed by electron abstraction from the π-system of the aryl groups.

In order to investigate the mechanism of the ceric ammonium nitrate (CAN) oxidation of aryl alkyl hydrocarbons, a scheme was set up indicating



Scheme 10. Possible rate determining steps for the oxidation of 1,2-diarylethanes by CAN

four processes which could be the rate determining step in the oxidation.

The first experiment was devised to differentiate between α-hydrogen atom abstraction as the rate determining process as opposed to radical cation formation as the rate determining step. Since it has been established by Wiberg and Evans (234) that α-hydrogen atom abstraction is the rate determining process in the oxidation of aryl alkanes by chromium(VI) oxide and it has been shown that 2,3-diphenyl-2,3-dimethylbutane is oxidized very slowly by chromium(VI) oxide (248), a competitive oxidation of 2,3-diphenyl-2,3-dimethylbutane _versus_ 1,2-diphenylethane was performed. If therefore, hydrogen abstraction is the rate determining process, the relative rate of oxidation of 2,3-diphenyl-2,3-dimethylbutane _versus_ 1,2-diphenylethane should be much less than 1. The relative rate of oxidation $k_{BC}/k_{BB} = 5.45 \pm 0.74$ however, which indicates that a process other than hydrogen atom abstraction is rate determining for these oxidations.

This result also tends to rule out proton loss after initial radical cation formation as the rate determining process. If proton loss was rate determining in the oxidation of 1,2-diphenylethane, the corresponding process in the case of 2,3-diphenyl-2,3-dimethylbutane would be loss of a methyl cation, an unfavorable process in solution (249). Therefore, 2,3-diphenyl-2,3-dimethylbutane should not be oxidized as fast as 1,2-diphenylethane unless there is a change in the mechanism of the oxidation.

In order to differentiate between radical cation formation as the rate determining process and cleavage of the central carbon-carbon bond after initial radical cation formation as the rate determining process, a Hammett correlation was determined. If radical cation formation is the rate determining process, a correlation with σ^+ should be observed as each aryl group is isolated from the other by the ethylene bridge. If, on the other hand, cleavage of the central carbon-carbon bond is the rate determining process, both groups should participate; one stabilizing a benzylic radical and the other stabilizing a benzylic cation and a correlation with $(\sigma^+ + \sigma^+)$ should be observed. As can be seen from Figures 4 and 5 , the correlation with σ^+ and with $(\sigma^+ + \sigma^+)$ are equally good. If, however, the results from the competitive oxidation involving 1,2-di-p-chlorophenylethane versus 1,2-diphenylethane[1] are not considered; the correlation with σ is much better than the correlation with $(\sigma^+ + \sigma^+)$ (Table 31). This result generates some support for radical cation formation as the rate determining process.

Further support for radical cation formation as the rate determining process rather than cleavage of the central carbon-carbon bond as the rate determining process can be obtained by considering the relative rates of a series of three 1,2-diarylethanes: 1,2-di-p-tolylethane, 1-p-tolyl-2-phenylethane and 1,2-diphenylethane. If cleavage to the benzyl radical and benzyl cation is the rate determining process and one assumes that the activated complex is symmetrical, the probability that the radical will preferentially be generated at one benzylic position is 0.5. If then,

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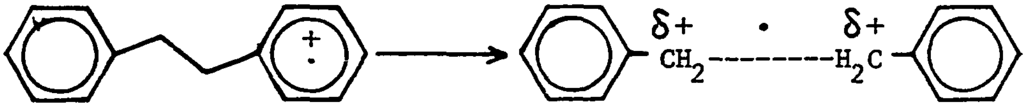
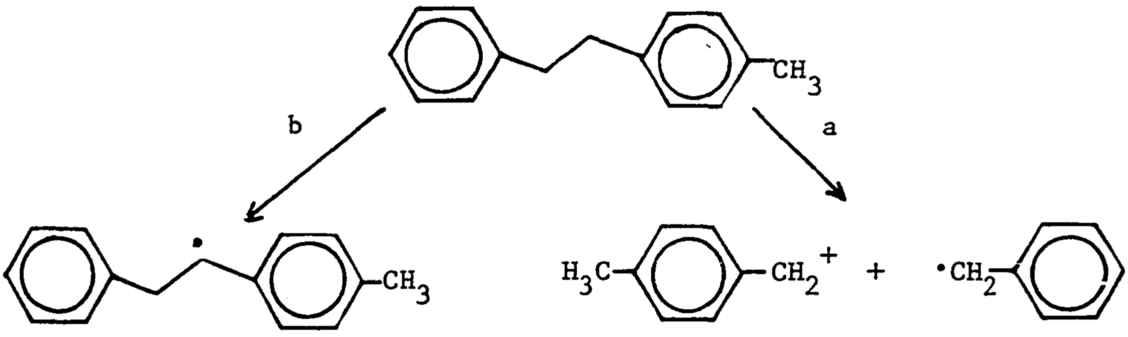
[1] The error in measuring the final concentration of the 1,2-diarylethanes in the competitive oxidations is large enough that the accuracy of the value for $k_{m\text{-}Cl}/k_H$ is in doubt.



the relative rate of oxidation for 1-p-tolyl-2-phenylethane versus 1,2-diphenylethane is represented by X, the relative rate for the oxidation of 1,2-di-p-tolylethane versus 1,p-tolyl-2-phenylethane should also be X as introduction of the second methyl substituent should have the same effect on the rate as the first methyl group. It further follows that the relative rate for the oxidation of 1,2-di-p-tolylethane versus 1,2-diphenylethane should equal X^2.

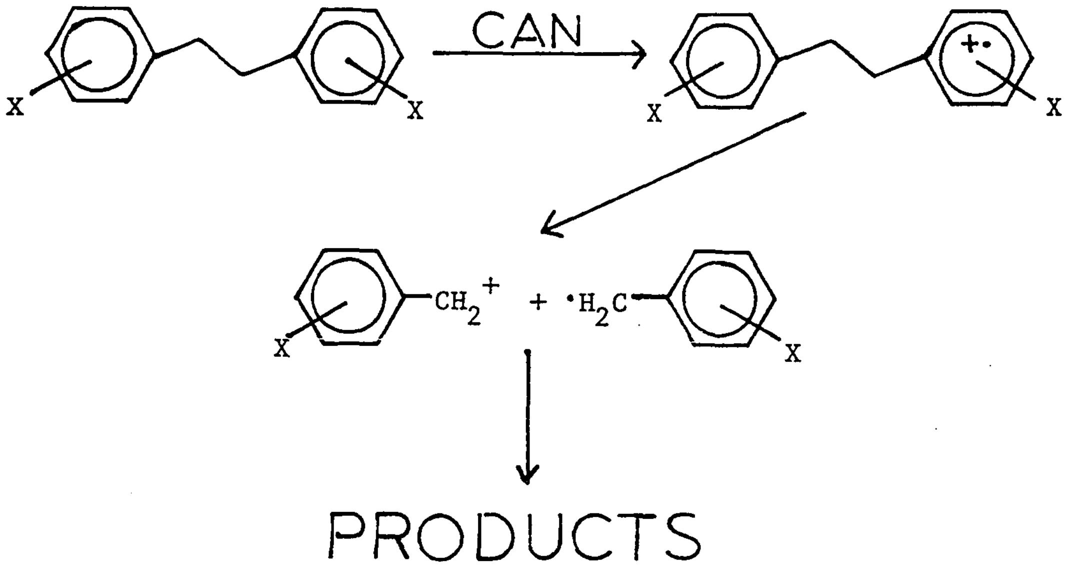
If, however, radical cation formation is the rate determining process, the addition of the second methyl substituent should only have a statistical effect on the rate as it only provides a second site for radical cation formation. In this case, if the relative rate of oxidation of 1-p-tolyl-2-phenylethane versus 1,2-diphenylethane is represented by X, the relative rate of oxidation of 1,2-di-p-tolylethane versus 1-p-tolyl-2-phenylethane should be 2.0. Similarly, the relative rate of oxidation of 1,2-di-p-tolylethane versus 1,2-diphenylethane should equal 2X. The results from the competitive oxidations presented in Table 31 show that the data are more consistent with the formation of a radical cation in the rate determining process than with cleavage of the central carbon-carbon bond as the rate determining process.

The generation of cleavage products from the oxidation of the 1,2-diarylethanes could conceivably arise by one of two different pathways: a) cleavage to benzylic radical and benzylic cation after initial radical cation formation or b) loss of a proton to generate a radical species which is further oxidized to the cation by cerium(IV). The cation is captured by water to generate an alcohol which is further oxidized by CAN to provide the observed products. By analysis of the product mixture from the oxidation of 1-p-tolyl-2-phenylethane, one would be able to differentiate between the two pathways, a and b. If proton loss to generate a 1-p-tolyl-2-phenylethyl radical followed by eventual formation of 1-p-tolyl-2-phenylethanol was operative, one would expect no p-methylbenzyl alcohol or p-methylbenzyl nitrate to be found in the product mixture since the oxidation of 1-p-tolyl-2-phenylethanol (65) by CAN leads to only benzyl nitrate, benzyl alcohol and p-tolualdehyde as products. The generation of 1-p-tolyl-2-phenylethanol is reasonable in view of the large relative rate difference for the oxidation of 1-p-tolyl-2-phenyl-



ethene versus 1,2-diphenylethane, which indicates virtually exclusive formation of the radical cation on the p-tolyl ring. If cleavage was occurring, however, one would expect to find all possible products generated from both portions of the 1,2-diarylethane, which is the result obtained.

Therefore, a possible mechanism for the oxidation of 1,2-diarylethanes by CAN in aqueous acetonitrile is shown in Scheme 11.



Scheme 11. Proposed mechanism for the oxidation of 1,2-diarylethanes by CAN

The cleavage process, which occurs after initial radical cation formation in the rate determining step, is analogous to the mass spectral process which occurs for 1,2-diphenylethane (250). The oxidation of 1,2-diarylethanes by CAN is only the second example of analogies between mass spectrometry and solution phase oxidations (251) and the first involving a metal ion oxidant.

EXPERIMENTAL

Equipment

All equipment used is described on page 69.

Methods

Glpc analyses were carried out using a 1 m x 6.25 mm aluminum column packed with 20% SE-52 (phenyl) on Chromasorb W (80/100 mesh). Conditions for the analyses were: 275° injector temperature, 300° detector temperature and 60 ml/min helium flow rate. The column temperature for the analyses involving 4,4'-dimethylbibenzyl, 4-methylbibenzyl or bibenzyl was 150°, while the column temperature for the analyses with 3,3'-dichlorobibenzyl or 4,4'-dichlorobibenzyl present was maintained at 150° until the non-chlorinated products were eluted and was then raised to 175°. Peak areas were determined by xeroxing the chromatograms and cutting and weighing the peaks.

Materials

Reagents were used as obtained from commercial sources unless purification procedures are noted.

Table 32. Commercial chemicals obtained

Chemical	Source
Ceric ammonium nitrate (CAN)	G. F. Smith Chemical Co.
Benzyl chloride	Aldrich
_p_-Methylbenzyl chloride	Aldrich
_p_-Chlorobenzyl chloride	Aldrich
_m_-Chlorobenzyl bromide	Aldrich
_p_-Methoxybenzyl alcohol	Aldrich
Bibenzyl	Aldrich
Diphenylmethane[a]	Aldrich

[a] Distilled before use.

Prepared Compounds

4,4'-Dimethylbibenzyl To 2.3 g magnesium in 50 ml anhydrous ether was added 15 g of p-methylbenzyl chloride at a rate that the ether gently refluxed. After stirring for 1 additional hour, another 15 g of p-methylbenzyl chloride was added and the reaction mixture was allowed to stir overnight. The mixture was hydrolyzed with saturated aqueous ammonium chloride solution and the ether layer was separated. The aqueous layer was extracted 1 time with 50 ml of ether and the combined ether extracts were dried ($MgSO_4$). The ether was removed at reduced pressure by rotary evaporation to give 10.1 g of the bibenzyl: mp 83-4° (lit (252) 85°); nmr (CCl_4) δ 2.30 (s, 6H), 2.80 (s, 4H) and 6.98 (s, 8H).

4,4'-Dichlorobibenzyl To 2.6 g magnesium in 50 ml anhydrous ether was added 16.1 g of p-chlorobenzyl chloride and the resulting mixture was stirred for 1 additional hour. At this time 16.1 g of p-chlorobenzyl chloride in 20 ml ether was added and the mixture was stirred at room temperature for 2 days. The mixture was decomposed with saturated aqueous ammonium chloride solution and the ether layer removed. The aqueous layer was extracted 1 time with 50 ml ether, the combined ether extracts were dried ($MgSO_4$) and the ether was removed at reduced pressure by rotary evaporation to yield a solid residue. The residue was chromatographed on alumina with hexane as elutant to give 8.5 g (34%) of the bibenzyl: mp 110-111° (lit (253) 112°); nmr (CCl_4) δ 2.80 (s, 4H), 6.89 (m, 4H) and 7.11 (m, 4H).

3,3'-Dichlorobibenzyl To 1.8 g of magnesium in 50 ml ether was added 15 g of 3-chlorobenzyl bromide dropwise. After the addition was completed, the mixture was stirred 1 hour more and 15 g 3-chlorobenzyl bromide in 25 ml ether was added. The mixture was stirred at room temperature for 24 hours and decomposed with saturated aqueous ammonium chloride solution. The ether layer was removed and the aqueous layer was extracted 1 time with 50 ml ether. The combined ether extracts were dried ($MgSO_4$) and the ether was removed at reduced pressure by rotary evaporation to yield a solid residue. The residue was chromatographed on alumina with hexane as elutant to give 8.2 g (32%) of the bibenzyl: mp 98-9°; nmr (CCl_4) δ 2.78 (s, 4H) and 7.10 (m, 8H); ir (CCl_4) cm^{-1} 3045 (m), 2950 (m), 2860 (m), 1600 (s), 1480 (s), 1433 (s), 1090 (m), 1080 (m), 880 (m), 865 (m) and 695 (s); mass spectrum (70 eV) m/e (rel. intensity) 254 (3), 252 (13), 250 (20), 128 (3), 127 (38), 126 (10) and 125 (100); Anal.: calc. for $C_{14}H_{12}Cl_2$: C, 66.93; H, 4.82; Cl, 28.25. Found: C, 66.95; H, 4.77; Cl, 28.12.

p-Methylbenzylphenyl ketone A modification of the procedure of Allen and Barker (254) was used; to 17.4 g of p-methylphenylacetic acid was added 8.4 g phosphorus trichloride and the mixture was heated on a steambath for 1 hour. While still warm, 100 ml benzene was added and the benzene solution decanted onto 20 g anhydrous aluminum trichloride with external cooling. After the addition was completed, the mixture was allowed to reflux for 1 hour and poured onto 100 g ice and 50 g concentrated hydrochloric acid. The aqueous 1 layer was extracted 1 time with 100 ml benzene and 1 time with 100 ml ether. The combined organic layers were washed 1 time with 100 ml saturated aqueous sodium chloride solution and dried over 12 g anhydrous calcium chloride. The benzene and ether were removed at reduced pressure by rotary evaporation and the residue was recrystallized from ethanol to give 21.0 g (83%) of the ketone: mp 97-8°

(lit (255) 97°); nmr (CCl_4) δ 2.23 (s, 3H), 4.03 (s, 2H), 6.97 (s, 4H), 7.30 (m, 3H) and 7.80 (m, 2H).

4-Methylbibenzyl To 1.4 g 10% palladium on charcoal was added 14 g *p*-methylbenzylphenyl ketone in 75 ml 50-50 ethanol ethyl acetate (by volume) which was 10^{-3} M in hydrochloric acid. The mixture was hydrogenated for 12 hours, the solution filtered and dried ($MgSO_4$). The ethanol and ethyl acetate were removed at reduced pressure by rotary evaporation and the residue was chromatographed on alumina with hexane as elutant to give 11.8 g (90%) of the bibenzyl: mp 25° (lit(256) 27°); nmr (CCl_4) δ 2.18 (s, 3H), 2.75 (s, 4H), 6.85 (s, 4H) and 6.94 (s, 5H).

4-Methoxybenzylchloride To 36 g of 4-methoxybenzyl alcohol in 20 ml pyridine was added 32 g thionylchloride dropwise with stirring. During the addition and for 3 hours afterwards, the reaction temperature was maintained below 30°. The mixture was poured into 100 ml water and extracted 2 times with 100 ml ether portions. The combined ether extractions were washed 2 times with 50 ml portions of water and 2 times with 50 ml portions of saturated aqueous ammonium chloride solution. The ether was dried ($MgSO_4$) and removed under reduced pressure by rotary evaporation to yield 22.5 g (56%) of the chloride: nmr (CCl_4) δ 3.37 (s, 3H), 4.43 (s, 2H), 6.68 (m, 2H) and 7.23 (m, 2H).

4,4'-Dimethoxybibenzyl To 3.5 g magnesium in 50 ml of ether was added 25.5 g 4-methoxybenzyl chloride in 25 ml of ether. The reaction was warmed slightly to initiate the reaction and the benzyl chloride was then added dropwise at a rate that the ether gently refluxed. After the addition was completed, the reaction was stirred at room temperature for 1 hour. Excess Grignard reagent was decomposed with saturated aqueous ammonium chloride solution. The ether layer separated and was removed and the aqueous layer was extracted 2 times with 25 ml portions of ether. The combined ether extractions were combined and washed 1 time with 50 ml of water. The ether was dried ($MgSO_4$) and removed at reduced pressure by rotary evaporation. The residue was chromatographed on alumina using hexane as elutant to give 12.4 g (40%) of the bibenzyl: mp 125-6° (lit (257) 125°); nmr ($CDCl_3$) δ 2.77 (s, 4H), 3.70 (s, 6H), 6.67 (m, 4H) and 6.97 (m, 4H).

Cerium(IV) Oxidations

Diarylbibenzyls

To 2.00 mmoles of bibenzyl in 40 ml of 70% aqueous acetonitrile (0.36 N HNO_3) was added 4.4 g of CAN in 10 ml of 70% aqueous acetonitrile. The reaction mixture was heated on a steam bath and allowed to reflux until the color of the solution had faded to pale yellow. The solution was cooled, standard added and poured into 50 ml of water. The mixture was extracted 3 times with 25 ml of ether. The combined ether extracts were washed 3 times with 10 ml of 1.2 N aqueous sodium hydroxide solution and 3 times with 25 ml of water. The ether solution was dried ($MgSO_4$) and the ether was removed on a rotary evaporator at reduced pressure. The residue was dissolved in CCl_4 for nmr analysis.

4-Methylbibenzyl

To approximately 2.00 mmoles (weighed accurately) 4-methylbibenzyl in 40 ml 70% aqueous acetonitrile (0.36 N HNO_3) was added 5.5 g ceric ammonium nitrate in 10 ml 70% aqueous acetonitrile (0.36 N HNO_3) and the mixture was heated on a steam bath. The reaction mixture was allowed to

Table 33. Analysis of the oxidations to determine the product yields in the oxidation of 1,2-diarylethanes with CAN at 80° in 70% aqueous acetonitrile (0.36 N HNO_3)

Diarylethane	Standard[a]	Area/H			
	(mmoles)	Std.	ArCHO	$ArCH_2OH$	$ArCH_2ONO_2$
$(C_6H_5CH_2)_2$	1.58	68.0	39.0	2.0	26.7
	1.52	60.2	40.0	1.5	23.4
	2.69	78.0	35.0	2.0	22.5
$(CH_3OC_6H_5CH_2)_2$	1.55	86.9	127.0	27.2	3.8
	1.51	87.5	130.0	27.5	1.5
$(CH_3C_6H_5CH_2)_2$	1.54	89.3	101.4	24.0	66.4
	1.56	90.2	100.8	22.3	68.1

[a] Diphenylmethane was used as standard in all runs.

reflux until the color of the solution had faded to pale yellow (about 45 mintues). The reaction mixture was cooled and standard, diphenylmethane, was added. The mixture was poured into 50 ml of water and extracted 3 times with 25 ml portions of ether. The combined ether extracts were washed 3 times with 10 ml portions of 1.2 N aqueous sodium hydroxide solution, 3 times with 25 ml portions of water and 1 time with 25 ml of saturated aqueous sodium chloride solution. The ether was dried ($MgSO_4$) and removed at reduced pressure by rotary evaporation. The residue was taken up in carbon tetrachloride and analyzed by nmr. After the yields of the combined products were obtained, a second nmr spectrum was taken on a sweep width of 100 Hz to allow for the calculation of the yield of each individual product. The nmr spectrum for runs 1 and 2 were xeroxed and the analysis for the individual products was performed using a cut and weigh technique. The results are presented in Table 34.

Table 34. Product yields from the oxidation of 4-methylbibenzyl by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

Product area/H				mmoles of product			
Std.	ArOH	$ArONO_2$	ArCHO	Std.	ArOH	$ArONO_2$	ArCHO
42.2	15.8	51.8	76.0	0.92	0.24	1.00	1.64
55.0	13.0	55.0	90.0	1.00	0.24	1.00	1.65
79.0	17.8	74.7	123.0	1.04	0.23	0.99	1.62

Table 35. Yield of the individual products from the oxidation of 4-methylbibenzyl in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

Spectrum	Product	Peak weight	mmoles of product
1	ϕCH_2OH	0.0305	0.14
2		0.0202	0.14
1	$p\text{-}CH_3\phi CH_2OH$	0.0250	0.10
2		0.0140	0.10
1	ϕCH_2ONO_2	0.1594	0.81
2		0.1160	0.80
1	$p\text{-}CH_3\phi CH_2ONO_2$	0.0462	0.19
2		0.0405	0.20
1	ϕCHO	0.0300	0.35
2		0.0240	0.39
1	$p\text{-}CH_3\phi CHO$	0.1400	1.29
2		0.0951	1.26

Competitive Oxidation of Bibenzyl and Bicumyl

To 2.00 mmoles of each hydrocarbon in 40 ml 70% aqueous acetonitrile (0.36 N HNO_3) was added 5.5 g CAN in 10 ml 70% aqueous acetonitrile (0.36 N HNO_3). The mixture was heated to reflux and allowed to reflux until the solution had faded to pale yellow. The mixture was cooled, standard (diphenylmethane) added and poured into 50 ml of water. The mixture was extracted 3 times with 25 ml portions of pentane and the combined pentane extracts were washed 3 times with 10 ml portions of 1.2 N sodium hydroxide solution and 1 time with 25 ml saturated sodium chloride solution. The pentane was dried ($MgSO_4$) and removed under reduced pressure. The residue was taken up in carbon tetrachloride and analyzed by nmr.

Table 36. Competitive oxidation of bicumyl *versus* bibenzyl in 70% aqueous acetonitrile (0.36 N HNO_3) by CAN at 80°

Run	Peak area/H			mmoles		
	Std.	Bicumyl	Bibenzyl	Std.	Bicumyl	Bibenzyl
1	17.5	14.1	17.9	1.83	1.47	1.87
2	24.1	16.6	22.7	1.99	1.37	1.87
3	21.1	14.3	20.2	1.96	1.33	1.87

Competition Experiments

To 2.00 mmoles of each diarylethane in 40 ml of 70% aqueous acetonitrile (0.36 N HNO_3) was added 5.5 g of CAN in 10 ml of 70% aqueous acetonitrile (0.36 N HNO_3). The reaction mixture was heated on a steam bath at reflux until the solution had faded to pale yellow. The mixture was allowed to cool and standard (diphenylmethane) was added. The mixture was poured into 50 ml of water and extracted 3 times with 25 ml portions of pentane. The combined pentane extracts were washed 3 times with 10 ml portions of 1.2 N sodium hydroxide solution and 1 time with 25 ml of saturated sodium chloride solution. The pentane was dried ($MgSO_4$) and removed at reduced pressure. The residue was taken up in 5 ml of pentane and analyzed by glpc.

Table 37. Competitive oxidation of 1,2-diarylethanes by CAN in 70% aqueous acetonitrile (0.36 N HNO_3) at 80°

1,2-Diarylethane		Peak area			mmoles[a]	
D_1	D_2	Std.	D_1	D_2	D_1	D_2
p-CH_3,p-CH_3	p-CH_3,H	0.1186	0.0541	0.1143	0.584	1.16
		0.1196	0.0562	0.1139	0.593	1.17
		0.1230	0.0515	0.1090	0.529	1.12
p-CH_3,H	H,H	0.1244	0.0119	0.1933	0.116	1.82
		0.1251	0.0126	0.1932	0.117	1.82
		0.1242	0.0131	0.2016	0.119	1.82
p-Cl,p-Cl	H,H	0.1090	0.1686	0.1328	1.80	1.44
		0.1190	0.1667	0.1358	1.83	1.49
		0.1197	0.1665	0.1178	1.78	1.26
m-Cl,m-Cl	H,H	0.1118	0.1690	0.0982	1.96	1.14
		0.1297	0.2195	0.1271	1.95	1.13
		0.1231	0.2092	0.1202	1.95	1.12

[a] Corrected for extraction ratios and detector response.

SUMMARY

The mechanism of the oxidation of substituted phenylacetic acids was studied by competitive oxidations of the acids with ceric ammonium nitrate. The relative rate data were correlated with σ values to generate a ρ value of -2.92 ± 0.48. As this ρ value is more negative than the usual values for benzylic radical processes, the formation of benzylic radicals as intermediates in the oxidation was confirmed by radical trapping studies with oxygen. The high negative ρ value and the correlation with σ^+ was taken to indicate that considerable carbenium ion character is present at the benzylic position in the activated complex.

The oxidation of 2,5-diarylfurans and 2-phenyl-5-alkylfurans generate good to excellent yields of cis-1,4-diaryl-2-butene-1,4-diones and 1-phenyl-4-alkyl-2-butene-1,4-diones. The oxidation of 2,5-dimethylfuran with ceric ammonium nitrate in methanol yields 2-methoxymethyl-5-methylfuran while the addition of methoxide anion or cyanide anion to the reaction mixture generates additional products, cis and trans-2,5-dimethoxy-2,5-dimethyl-2,5-dihydrofuran.

A mechanistic study was undertaken using competitive oxidations of 2,5-diarylfurans and correlating the relative rates with σ values. The correlation was best with $(\sigma^+ + \sigma^+)$ which indicated that both aryl groups were involved in stabilization of the activated complex. From this, a mechanism has been postulated involving radical cation formation as the rate determining process by electron transfer from the furan nucleus. The processes which occur after initial radical cation

formation are dependent upon both the solvent and the substrate.

The reaction of olefins with ceric ammonium nitrate generates 1,2-dinitrate and 1-acetamido-2-nitrate products. The addition of the nitrate has been shown to occur trans by the reduction of 1,2-indandiol-1,2-dinitrate to trans-1,2-indandiol. The addition of the nitrates is stereospecific as only meso-1,2-stilbenediol-1,2-dinitrate is produced by the oxidation of trans-stilbene, while d,l-1,2-stilbenediol-1,2-dinitrate is produced in the oxidation of cis-stilbene. The oxidation of trans-β-methylstyrene also produces only one of two possible isomers, which by analogy with the stilbene system has tentatively been identified as erythro-1,2-n-propylbenzenediol-1,2-dinitrate. The stereospecificity of the reaction is explained by the formation of bridged nitrates as radical or cationic intermediates.

Substituted bibenzyls are oxidized by ceric ammonium nitrate to yield cleavage products: substituted benzaldehydes, substituted benzyl alcohols and substituted benzyl nitrates. The mechanism of the oxidation was studied by competitive oxidations of substituted bibenzyls and the relative rate data was subjected to a Hammett $\rho\sigma$ correlation. In addition, the relative rates of three substituted bibenzyls were considered separately. The oxidation of substituted bibenzyls is postulated as proceeding through initial radical cation formation by electron transfer from the aromatic nucleus, followed by a cleavage process which generates a benzyl radical and benzyl cation in one step. This analogy with mass spectral processes, is the first observed for a metal ion oxidation in solution.

BIBLIOGRAPHY

1. Becker, H. and A. Bistrzycki, Helvetica Chim. Acta, 2, 111 (1919).

2. Fisher, F. and H. Schrader, Ges. Abhandl. Kennt. Kohle, 5, 307 (1921) CA 17, 2572 (1923).

3. Grob, C. A., M. Ohta, E. Renk, and A. Weiss, Helv. Chim. Acta, 41, 1191 (1958).

4. Doering, W. von E., J. Amer. Chem. Soc., 74, 4370 (1952).

5. Plieninger, H. and W. Lehmert, Chem. Ber., 100, 2427 (1967).

6. Radlick, P., R. Klen, S. Spurlock, J. J. Sims, E. E. van Tamelen and T. Whitesides, Tetrahedron Letters, 5117 (1968).

7. Westberg, H. H. and H. J. Dauben, Tetrahedron Letters, 5123 (1968).

8. Kharash, M. S., H. N. Fridlander and W. H. Urry, J. Org. Chem., 16, 533 (1951).

9. Mosher, W. A. and C. L. Kehr, J. Amer. Chem. Soc., 75, 3172 (1952).

10. Corey, E. J. and J. Cassanova, J. Amer. Chem. Soc., 85, 165 (1963).

11. Jacques, J., C. Weidmann and A. Horeau, Bull. Soc. Chim. France, 424 (1959).

12. Kochi, J. K., J. Amer. Chem. Soc., 87, 1811 (1965).

13. Kochi, J. K., J. Amer. Chem. Soc., 87, 3609 (1965).

14. Kochi, J. K., J. Org. Chem., 30, 3265 (1965).

15. Kochi, J. K., J. D. Bacha, and T. W. Bethea III, J. Amer. Chem. Soc., 89, 6538 (1967).

16. Bacha, J. D. and J. K. Kochi, Tetrahedron, 24, 2215 (1968).

17. Kochi, J. K., R. A. Sheldon, and S. S. Lande, Tetrahedron, 25, 1197 (1969).

18. Davies, D. I. and C. Waring, J. Chem. Soc. B, 1639 (1967).

19. Davies, D. I. and C. Waring, J. Chem. Soc. B, 1865 (1968).

20. Davies, D. I. and C. Waring, J. Chem. Soc. B, 2332 (1968).

21. Shono, T., I. Nishiguchi, and R. Oda, Tetrahedron Letters, 373 (1970).

22. Reidhenbacher, P. H., M. Y. Liu and P. S. Skell, J. Amer. Chem. Soc., 90, 1816 (1968).

23. Eberson, L., J. Amer. Chem. Soc., 91, 2402 (1969).

24. Keating, J. T. and P. S. Skell, J. Org. Chem., 34, 1479 (1969).

25. Traynham, J. G. and J. S. Dehn, J. Amer. Chem. Soc., 89, 2139 (1967).

26. Gassman, P. G. and F. V. Zalar, J. Amer. Chem. Soc., 88, 2252 (1966).

27. Coleman, J. P., J. H. P. Utley and B. C. L. Weedon, Chem. Commun., 438 (1971).

28. Coleman, J. P. and L. Eberson, Chem. Commun., 1300 (1971).

29. Clifford, A. A. and W. A. Waters, J. Chem. Soc., 2796 (1965).

30. Sharan, P. R., P. Smith and W. A. Waters, J. Chem. Soc. B, 1322 (1968).

31. Smith, P. and W. A. Waters, J. Chem. Soc., 462 (1969).

32. Starnes, W. H., Jr., J. Org. Chem., 31, 1436 (1966).

33. Lande, S. S. and J. K. Kochi, J. Amer. Chem. Soc., 90, 5196 (1968).

34. Anderson, J. M. and J. K. Kochi, J. Org. Chem., 35, 986 (1970).

35. Anderson, J. M. and J. K. Kochi, J. Amer. Chem. Soc., 92, 1651 (1970).

36. Anderson, J. M. and J. K. Kochi, J. Amer. Chem. Soc., 92, 2450 (1970).

37. Van Helden, R. and E. C. Kooyman, Rec. Trav. Chim. 80, 57 (1961).

38. Van Helden, R., A. F. Bickel and E. C. Kooyman, Rec. Trav. Chim., 80, 1237 (1961).

39. Bacha, J. D. and J. K. Kochi, J. Org. Chem., 33, 75 (1968).

40. Khan, S. M., A. A. Khan and M. A. Bee, J. Prakt. Chem., 311, 383 (1969).

41. Sheldon, R. A. and J. K. Kochi, J. Amer. Chem. Soc., 90, 6688 (1968).

42. Mathai, I. M. and R. Vasudevan, J. Chem. Soc. B, 1361 (1970).

43. Cramer, J. and W. S. Trahanovsky, unpublished results.

44. Trahanovsky, W. S., J. Cramer and D. W. Brixius, Abstracts of Papers, 160th National Meeting of the American Chemical Society, Chicago, Ill., Sept. 1970, ORGN 144.

45. Fichter, Fr. and H. Lapin, Helv. Chim. Acta, 12, 993 (1929).

46. Fichter, Fr. and H. F. Suenderhaul, Helv. Chim. Acta, 16, 338 (1933).

47. Fichter, Fr. and J. Hees, Helv. Chim. Acta, 18, 704 (1935).

48. Fichter, Fr. and J. Hees, Helv. Chim. Acta, 19, 149 (1936).

49. Fichter, Fr. and L. Panizzon, Helv. Chim. Acta, 15, 996 (1932).

50. Russell, J. and R. H. Thomson, J. Chem. Soc., 3379 (1962).

51. Brown, P. M., J. Russell, R. H. Thomson and A. G. Wylie, J. Chem. Soc. C, 842 (1968).

52. Tanner, D. D. and S. A. A. Osman, J. Amer. Chem. Soc., 90, 6572 (1968).

53. Norman, R. O. C., P. M. Storey and P. R. West, J. Chem. Soc. B, 1087 (1970).

54. Norman, R. O. C. and P. M. Storey, J. Chem. Soc. B, 1099 (1970).

55. Cohen, T., I. H. Song and J. H. Fager, Tetrahedron Letters, 237 (1965).

56. Cohen, T., I. H. Song, J. H. Fager and G. L. Deets, J. Amer. Chem. Soc., 89, 4968 (1967).

57. Brown, H. C. and Y. Okamoto, J. Amer. Chem. Soc., 80, 4979 (1958).

58. Beineke, T. A. and J. Delgaudio, Inorg. Chem., 7, 715 (1968).

59. Miller, J. T. and D. E. Irish, Can. J. Chem., 45, 147 (1967).

60. Henshall, A., Diss. Abstr., 24, 5023 (1964).

61. Larsen, R. D. and G. H. Brown, J. Phys. Chem., 68, 3060 (1964).

62. Fischer, A., B. R. Mann and J. Vaughan, J. Chem. Soc., 1093 (1961).

63. Jaffe, H. H., Chem. Rev., 53, 191 (1953).

64. Swain, C. G. and E. L. Lupton, J. Amer. Chem. Soc., 90, 4328 (1968).

65. Nave, P. M., Ph.D. thesis, Iowa State University, Ames, Iowa, 1969.

66. Bartlett, P. D. and C. Ruchardt, J. Amer. Chem. Soc., 82, 1756 (1960).

67. Howard, J. A. and K. U. Ingold, Can. J. Chem., 41, 1744 (1963).

68. Russell, G. A. and R. C. Williamson, Jr., J. Amer. Chem. Soc., 86, 2357 (1964).

69. Huang, R. L. and K. H. Lee, J. Chem. Soc. C, 935 (1966).

70. Gilliom, R. P. and B. F. Ward, Jr., J. Amer. Chem. Soc., 87, 3944 (1965).

71. Brown, H. C., R. Bernheimer, C. J. Kim, and S. E. Scheppele, J. Amer. Chem. Soc., 89, 370 (1967).

72. Shiner, V. J., Jr., W. E. Buddenbaum, B. L. Murr, and G. Lamaty, J. Amer. Chem. Soc., 90, 418 (1968).

73. Noyee, D. S. and G. V. Kaiser, J. Org. Chem., 34, 1008 (1969).

74. Wiberg, K. B. and P. C. Ford, J. Amer. Chem. Soc., 91, 124 (1969).

75. Richardson, W. H. in "Oxidation in Organic Chemistry", Part A, K. B. Wiberg, Ed., Academic Press, New York, N.Y., 1965, p. 244.

76. Russell, G. A., J. Amer. Chem. Soc., 79, 3871 (1957).

77. Ferris, A. F., K. W. McLean, J. G. Marks and W. D. Emmons, J. Amer. Chem. Soc., 75, 4078 (1953).

78. Baker, J. W. and W. S. Nathan, J. Chem. Soc., 236 (1936).

79. Richter, V. von, Chem. Ber., 4, 973 (1871).

80. Kawai, S., S. Tanaka and T. Nishiwaki, Nippon Kagaku Zasshi, 80, 340 (1959).

81. Traverso, G., and G. P. Pollini, Farmico (Pavia) Ed. Sci., 20, 813 (1965).

82. Zinnin, N., J. Prakt. Chem. (I), 101, 164 (1867).

83. Bailey, P. S., S. S. Bath, W. F. Thomsen, H. H. Nelson and E. E. Kawas, J. Org. Chem., 21, 297 (1956).

84. Bailey, P. S. and J. C. Smith, J. Org. Chem., 21, 628 (1956).

85. Bailey, P. S. and J. D. Christian, J. Amer. Chem. Soc., 71, 4122 (1949).

86. Lutz, R. E. and F. N. Wilder, J. Amer. Chem. Soc., 56, 978 (1934).

87. Lutz, R. E. and C. J. Kibler, J. Amer. Chem. Soc., 62, 1520 (1940).

88. Lutz, R. E. and W. P. Boyer, J. Amer. Chem. Soc., 63, 3189 (1941).

89. Pyatnitskii, M. P. and L. B. Lapkora, Zh. Prikl. Bhim., 36, 2290 (1963).

90. Lapkova, L. B., V. G. Kul'nevich and V. P. Gvozdetskaya, Zh. Prikl. Khim., 42, 1358 (1969).

91. Seebach, D., Chem. Ber., 96, 2712 (1963).

92. Lutz, R. E. and C. K. Dien, J. Org. Chem., 23, 1861 (1958).

93. Elming, N. and N. Clauson-Kaas, Acta Chem. Scand., 6, 535 (1962).

94. Elming, N., Acta Chem. Scand., 578 (1952).

95. Clauson-Kaas, N., Kgl. Danske Videnskab Selskab, Mat-fys. Medd, 24, 6 (1947).

96. Dien, C. K. and R. E. Lutz, J. Org. Chem., 22, 1356 (1957).

97. Jibben, B. P. and J. P. Wilbaut, Recueil Trav. Chim., Pays-Bas, 79, 342 (1960).

98. Bailey, P. S. and H. O. Colomb, Jr., J. Amer. Chem. Soc., 79, 4238 (1957).

99. White, H. M., H. O. Colomb, Jr., and P. S. Bailey, J. Org. Chem., 30, 481 (1965).

100. Bailey, P. S., H. M. White, and H. O. Colomb, Jr., J. Org. Chem., 30, 487 (1965).

101. Lutz, R. E., W. J. Welstead, Jr., R. G. Bass, and J. I. Dale, J. Org. Chem., 27, 1111 (1962).

102. Martel, J., C. R. Acad. Sci., Paris, 244, 626 (1957).

103. Wasserman, H. H. and A. Liberles, J. Amer. Chem. Soc., 82, 2086 (1960).

104. Holecek, V. and V. Horak, Coll. Czech. Chem. Commun., 27, 2717 (1962).

105. van der Merwe, J. P. and C. F. Garbers, J. S. African Chem. Inst., 17, 149 (1964).

106. Foote, C. S., S. Wexler, W. Ando and R. Higgins, J. Amer. Chem. Soc., 90, 975 (1968).

107. Foote, C. S. and S. Wexler, J. Amer. Chem. Soc., 90, 3879 (1964).

108. Lutz, R. E. and W. J. Welstead, Jr., J. Amer. Chem. Soc., 85, 755 (1963).

109. Clauson-Kaas, N. and J. Fakstorp, Acta Chem. Scand., 1, 216 (1947).

110. Catala, J. and J. Defaye, C. R. Acad. Sci., Paris, 258, 4094 (1964).

111. Ferland, J. M., Y. Lefebvre, R. Deghenghi and K. Wiesner, Tetrahedron Letters, 3617 (1966).

112. Lefebvre, Y., Tetrahedron Letters, 133 (1972).

113. Elming, N., Acta Chem. Scand., 6, 605 (1952).

114. Clauson-Kaas, N., F. Limborg and K. Glens, Acta Chem. Scand., 6, 531 (1952).

115. Clauson-Kaas, N., Acta Chem. Scand., 6, 569 (1952).

116. Elming, N., Acta Chem. Scand., 6, 572 (1952).

117. Baggaley, A. J. and R. Brettle, Chem. Commun., 108 (1966).

118. Baggaley, A. J. and R. Brettle, J. Chem. Soc. C, 969 (1968).

119. Ross, S. D., M. Finkelstein and J. J. Uebel, J. Org. Chem., 34, 1018 (1969).

120. Yoshida, K. and T. Fueno, Bull. Chem. Soc. Japan, 42, 2411 (1969).

121. Yoshida, K. and T. Fuena, J. Org. Chem., 36, 1523 (1971).

122. Trahanovsky, W. S., L. B. Young and M. D. Robbins, J. Amer. Chem. Soc., 91, 7089 (1969).

123. Muller, P., E. Katten and J. Rocek, J. Amer. Chem. Soc., 93, 7114 (1971).

124. Heiba, E. I., R. M. Dessau and W. J. Koehl, Jr., J. Amer. Chem. Soc., 91, 6830 (1969).

125. Dessau, R. M., S. Shih and E. I. Heiba, J. Amer. Chem. Soc., 92, 412 (1970).

126. Heiba, E. I., R. M. Dessau and W. J. Koehl, Jr., J. Amer. Chem. Soc., 91, 138 (1969).

127. Nave, P.-M. and W. S. Trahanovsky, J. Amer. Chem. Soc., 93, 4536 (1971).

128. Howell, B., Iowa State University, personal communication, 1972.

129. Sauer, J., H. Weist and A. Mielert, Z. Naturforsch., 17b, 203 (1962).

130. Sauer, J., D. Lang and H. Weist, Z. Naturforsch., 17b, 206 (1962).

131. Sauer, J., D. Lang and H. Weist, Chem. Ber., 97, 3208 (1964).

132. Huisgen, R., H. Seidl and I. Bruening, Chem. Ber., 102, 1102 (1969).

133. Clauson, Kaas, N., F. Limborg and J. Fakstorp, Acta Chem. Scand., 2, 109 (1948).

134. Levisalles, J., Bull. Soc. Chim. France, 997 (1957).

135. Hirsch, J. A. and A. J. Szur, Abstracts, 162nd National Meeting of the American Chemical Society, Washington, D.C., Sept. 1971, ORGN 30.

136. Conant, J. B. and R. E. Lutz, J. Amer. Chem. Soc., 45, 1303 (1923).

137. Lutz, R. E. and R. J. Rowlett, Jr., J. Amer. Chem. Soc., 70, 1360 (1948).

138. Nowlin, G., J. Amer. Chem. Soc., 72, 5754 (1950).

139. Grummitt, O., E. I. Becker and C. Miesse, Org. Syn. Coll. Vol. III, 109 (1955).

140. Lutz, R. E., J. Amer. Chem. Soc., 52, 3423 (1930).

141. Mathur, K. B. L., and H. S. Mehra, J. Chem. Soc., 2576 (1961).

142. Rips, R., C. Derappe and N. P. Bul-Hoi, J. Org. Chem., 25, 390 (1960).

143. Hellberger, J. H., Ann. Chem., 522, 269 (1936).

144. Paal, C., Chem. Ber., 17, 2760 (1884).

145. Lutz, R. E. and C. K. Dien, J. Org. Chem., 21, 551 (1956).

146. Boeseken, J., Recueil Trav. Chim., Pays-Bas, 41, 199 (1922).

147. Bleseken, J., Recueil Trav. Chim., Pays-Bas, 47, 683 (1928).

148. Wiberg, K. B. and K. A. Saegebarth, J. Amer. Chem. Soc., 79, 2822 (1957).

149. Burdon, J. and J. C. Tatlow, J. Appl. Chem. (London), 8, 293 (1958).

150. Suzuki, H., Bull. Chem. Soc. Japan, 33, 406 (1960).

151. Criegee, R., Ann. Chem., 481, 263 (1930).

152. Muller, R. and H. Plieninger, Chem. Ber., 92, 3009 (1959).

153. Criegee, R., P. Dimroth, K. Noll, R. Simon and C. Weis, Chem. Ber., 90, 1070 (1957).

154. Yukawa, Y. and M. Sakai, Bull. Chem. Soc. Japan, 36, 761 (1963).

155. Windaus, A. and U. Riemann, Z. Physiol. Chem., 274, 206 (1942).

156. Norman, R. O. C. and C. B. Thomas, J. Chem. Soc. B, 771 (1967).

157. Yukawa, Y. and N. Hayashi, Bull. Chem. Soc. Japan, 39, 2255 (1966).

158. Norman, R. O. C. and C. B. Thomas, J. Chem. Soc. B, 994 (1968).

159. Norman, R. O. C. and C. B. Thomas, J. Chem. Soc. B, 604 (1967).

160. Freeman, F., P. J. Cameron and R. H. DuBois, J. Org. Chem., 33, 3970 (1968).

161. Freeman, F., R. H. DuBois and N. J. Yamachika, Tetrahedron, 25, 3441 (1969).

162. Freeman, F. and N. J. Yamachika, Tetrahedron Letters, 3615 (1969).

163. Freeman, F. and N. J. Yamachika, J. Amer. Chem. Soc., 92, 3730 (1970).

164. Freeman, F., P. D. McCart and N. J. Yamachika, J. Amer. Chem. Soc., 92, 4621 (1970).

165. Freeman, F. and N. J. Yamachika, J. Amer. Chem. Soc., 94, 1214 (1972).

166. Hickinbottom, W. J., D. R. Hogg, D. Peters and D. G. M. Wood, J. Chem. Soc., 4400 (1954).

167. Garvin, J. H., J. Chem. Soc., 678 (1959).

168. Slack, R. and W. A. Waters, J. Chem. Soc., 594 (1949).

169. Butlerow, A., J. Russ. Phys. Chem. Soc., 12, 1482 (1879).

170. Awasthy, A. K. and J. Rocek, J. Amer. Chem. Soc., 91, 991 (1969).

171. Hickinbottom, W. J. and G. E. M. Moussa, J. Chem. Soc., 4195 (1957).

172. Hickinbottom, W. J. and D. G. M. Wood, J. Chem. Soc., 1906 (1953).

173. Hickinbottom, W. J., D. Peters and D. G. M. Wood, J. Chem. Soc., 1360 (1955).

174. Hickinbottom, W. J. and D. G. M. Wood, J. Chem. Soc., 1600 (1951).

175. Beyers, A. and W. J. Hickinbottom, J. Chem. Soc., 1334 (1948).

176. Schildknecht, H. and W. Fettinger, Ann. Chem., 659, 20 (1962).

177. Mosher, W. A., F. W. Steffgen and P. T. Lansbury, J. Org. Chem., 26, 670 (1961).

178. Kabbe, H. J., Ann. Chem., 656, 204 (1962).

179. Pande, K. C. and S. Winstein, Tetrahedron Letters, 3393 (1964).

180. Ouellette, R. J., G. Kordosky, C. Levin and S. Williams, J. Org. Chem., 34, 4104 (1969).

181. Bawn, C. E. H. and J. A. Sharp, J. Chem. Soc., 1854 (1957).

182. Bawn, C. E. H. and J. A. Sharp, J. Chem. Soc., 1866 (1957).

183. Dessau, R. M., J. Amer. Chem. Soc., 92, 6356 (1970).

184. Heiba, E. I. and R. M. Dessau, J. Amer. Chem. Soc., 93, 995 (1971).

185. Sykes, P. J. and F. J. Rutherford, Tetrahedron Letters, 3393 (1971).

186. Winstein, S. and R. Roberts, J. Amer. Chem. Soc., 75, 2297 (1953).

187. Cristol, S. J. and G. W. Nachtigall, J. Org. Chem., 32, 3738 (1967).

188. Wilt, J. W., G. Gutman, W. J. Ranus, Jr. and A. R. Zigman, J. Org. Chem., 32, 893 (1967).

189. Tori, K., A. Y. Hata, R. Muneyuki, T. Tsuji and H. Tanida, Tetrahedron Letters, 9 (1966).

190. Kochi, J. K., Rec. Chem. Prog., 27, 207 (1966).

191. Kochi, J. K., Science, 155, 3761 (1967).

192. Berson, J. A., "Carbonium Ion Rearrangements in Bridged Bicyclic Systems" in Molecular Rearrangements, Vol. I, P. deMayo, ed., Wiley Interscience, New York, N.Y., 1963, pp 111-233.

193. Robbins, M. D., Ph.D. thesis, Iowa State University, Ames, Iowa, 1971.

194. Trahanovsky, W. S. and J. Gilmore, Unpublished results.

195. Skell, P. S. and P. K. Freeman, J. Org. Chem., 29, 2524 (1964).

196. Readio, P. D. and P. S. Skell, J. Org. Chem., 31, 753 (1966).

197. LeBel, N. A., R. F. Czaja and A. DeBoer, J. Org. Chem., 34, 3112 (1969).

198. Roberts, J. D. and G. E. Kimball, J. Amer. Chem. Soc., 59, 947 (1937)

199. Fishbein, L., J. Amer. Chem. Soc., 79, 2959 (1957).

200. Hayward, L. D., M. Jackson and I. G. Csimadia, Can. J. Chem., 43, 1656 (1965).

201. Lancelot, C. J. and P. V. R. Schleyer, J. Amer. Chem. Soc., 91, 4291 (1969).

202. Lancelot, C. J., J. J. Harper and P. V. R. Schleyer, J. Amer. Chem. Soc., 91, 4294 (1969).

203. Lancelot, C. J. and P. V. R. Schleyer, J. Amer. Chem. Soc., 91, 4296 (1969).

204. Schleyer, P. V. R. and G. J. Lancelot, J. Amer. Chem. Soc., 91, 4297 (1969).

205. Harris, J. M., F. L. Schadt, P. V. R. Schleyer and C. J. Lancelot, J. Amer. Chem. Soc., 91, 7508 (1969).

206. Raber, D. J., J. M. Harris and P. V. R. Schleyer, J. Amer. Chem. Soc., 93, 4829 (1971).

207. Kingsbury, C. A. and D. C. Best, Tetrahedron Letters, 1499 (1967).

208. Friedman, L. and F. M. Logullo, J. Org. Chem., 34, 3089 (1969).

209. Zederic, J. A., H. Carpio and C. Djerassi, J. Amer. Chem. Soc., 82, 446 (1960).

210. Dimroth, O. and R. Schweizer, Chem. Ber., 56, 1376 (1923).

211. Detilleux, E. and J. Jarot, Bull. Soc. Roy. Sci. Liege, 24, 366 (1955).

212. Fieser, L. F., R. C. Clapp and W. H. Gaudt, J. Amer. Chem. Soc., 64, 2052 (1942).

213. Davies, D. I., J. Chem. Soc., 2351 (1963).

214. Heiba, E. I., R. M. Dessau and W. J. Koehl, Jr., J. Amer. Chem. Soc., 90, 1082 (1968).

215. Zonis, S. A., Sbornik Statei Obshchei Khim, 2, 1091 (1953).
CA 49, 5414 (1955.

216. Venkatachalapathy, M. S., R. Ramaswamy, and H. V. K. Udupa, Bull. Acad. Polon Sci. Ser SCE. Chim. geol. et geograph, 6, 487 (1958).

217. Andrulis, P. J., Jr., M. J. S. Dewar, R. Dietz and R. L. Hunt, J. Amer. Chem. Soc., 88, 5473 (1966).

218. Aratani, T. and M. J. S. Dewar, J. Amer. Chem. Soc., 88, 5479 (1966).

219. Andrulis, P. J., Jr., and M. J. S. Dewar, J. Amer. Chem. Soc., 88, 5483 (1966).

220. Cooper, T. A. and W. A. Waters, J. Chem. Soc. B, 687 (1967).

221. Cooper, T. A., A. A. Clifford, D. J. Mills and W. A. Waters, J. Chem. Soc. B, 793 (1966).

222. Sakota, K., Y. Kamiya and N. Ohta, Can. J. Chem., 47, 387 (1969).

223. Chester, A. W., Chem. Commun., 352 (1969).

224. Chester, A. W., J. Org. Chem., 35, 1797 (1970).

225. Gilman, H. C., G. Brannen and R. K. Ingham, J. Amer. Chem. Soc., 78, 1689 (1956).

226. Neuman, M. S. and L. L. Wood, J. Org. Chem., 23, 1236 (1958).

227. Friedman, L., Org. Syn., 43, 80 (1963).

228. Friedman, L., D. L. Fishel and H. Schecter, J. Org. Chem., 30, 1453 (1965).

229. Hartford, W. H. and M. Darrin, Chem. Rev. 58, 458 (1958).

230. Wiberg, K. B., B. Marshall and G. Foster, Tetrahedron Letters, 345 (1962).

231. Nishimura, T., Org. Syn., 36, 58 (1956).

232. Stockel, R. F. and D. M. Hall, J. Org. Chem., 27, 3705 (1962).

233. Schmidt, M. and H. Schmidbaur, Angew. Chem., 70, 704 (1958).

234. Wiberg, K. B. and R. J. Evans, Tetrahedron, 8, 313 (1960).

235. Stairs, R. A., Can. J. Chem., 42, 550 (1964).

236. Duffin, H. C. and R. B. Tucker, Tetrahedron, 24, 389 (1968).

237. Farbwerk vorm. Meister, Lucius and Bruning, German Patent 158,609 (1902). Chem. Zentr. (I), 76, 840 (1905).

238. Farbwerk vorm. Meister, Lucius and Bruning, German Patent 174,238 (1903). Chem. Zentr. (I), 77, 1297 (1906).

239. Ramaswamy, R., M. S. Venkatachalapathy and H. V. K. Udupa, Bull. Chem. Soc. Japan, 35, 1751 (1962).

240. Syper, L., Tetrahedron Letters, 4493 (1966).

241. Dust, L. A. and E. W. Gill, J. Chem. Soc. C, 1630 (1970).

242. Trahanovsky, W. S. and E. Peters, unpublished results.

243. Trahanovsky, W. S. and L. B. Young, J. Org. Chem., 31, 2033 (1966).

244. Young, L. B., Abstracts, 157th National Meeting of the American Chemical Society, Washington, D.C., April 1969, ORGN 69.

245. Eberson, L. and B. Olofsson, Acta Chem. Scand., 23, 2355 (1969).

246. Nyberg, K., Acta Chem. Scand., 24, 1609 (1970).

247. Lee, D. G., "Hydrocarbon Oxidation using Transition Metal Compounds" in Oxidation, Vol. I, R. L. Augustine, ed., Marcel Dekker, Inc., New York, N.Y., 1969, pp 1-51.

248. Foster, G. and W. J. Hickinbottom, J. Chem. Soc., 215 (1959).

249. March, J., "Advanced Organic Chemistry: Reactions, Mechanism and Structure", McGraw-Hill Book Company, New York, N.Y., 1968, p 126.

250. Eland, J. H. D. and C. J. Danby, J. Chem. Soc., 5935 (1965).

251. Miller, L. L., V. R. Koch, M. E. Lorscheid and J. F. Wolf, Tetrahedron Letters, 1389 (1971).

252. Meyer, H., and A. Hofmann, Manatsh. Chem. 37, 690 (1916).

253. Kade, R., J. Prakt. Chem., 19, 461 (1879).

254. Allen, C. F. H. and W. E. Barker, Org. Syn. Coll. Vol. II, 156 (1943).

255. Strassman, H., Chem. Ber., 22, 1229 (1889).

256. Mann, W., Chem. Ber., 14, 1645 (1881).

257. Buck, J. S. and S. S. Jenkins, J. Amer. Chem. Soc., 51, 2238 (1929).

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