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OXIDATIVE CLEAVAGE OF ALCOHOLS BY CERIUM(IV) AND CHROMIC ACID

by

Paul Michael Nave

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DOCTOR OF PHILOSOPHY

Major Subject: Organic Chemistry

Approved:

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In Charge of Major Work

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Dean of Graduate College

Iowa State University
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1969

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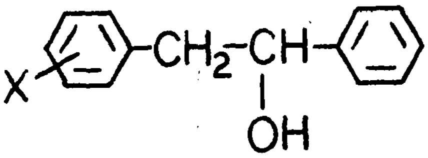
INTRODUCTION

The mechanism of the cerium(IV) oxidation of benzyl alcohols to benzaldehyde has been studied recently in this laboratory (1, 2). It was concluded that oxidation proceeds via rapid 1:1 alcohol-cerium(IV) complex formation followed by a rate determining unimolecular decomposition of the complex. It was found that ring substitution causes little change in the equilibrium constant of complex formation, but does have an effect on the decomposition step. The effect of the substituent can be correlated by a Hammett $\sigma\rho$ treatment to give a ρ value of -1.07 ± 0.28 using σ^+ values.

Whereas benzyl alcohols give good yields of benzaldehyde (3), with most other alcohols, aldehyde or ketone formation is very poor (4, 5). One of the most prominent oxidation routes is C-C cleavage. This cleavage reaction has been reported by several workers (5, 6, 7); however, a detailed mechanistic study was not made. The Hammett $\sigma\rho$ relationship has proved extremely useful as a mechanistic probe, and it was felt that this would be the best approach for studying the cleavage reaction. Thus, a series of 2-aryl-1-phenylethanols



was prepared and subjected to competitive oxidation by ceric ammonium nitrate in order to determine the effect of the substituent on the departing benzyl group.

During the course of this work, it became apparent that the results could serve as a model for cleavage by a one-electron process and be compared with the results obtained using more complex oxidants in which cleavage is always accompanied by other modes of oxidation. Since cleavage in chromic acid oxidations has been a subject of controversy (*vide infra*), the study of this process was undertaken.

The results obtained for the competitive oxidations of substituted 1,2-diphenylethanols with ceric ammonium nitrate and chromic acid were compared with the results obtained in an internal competition in which there were two modes of cleavage from the same molecule, in order to gain more information about the overall mechanism.

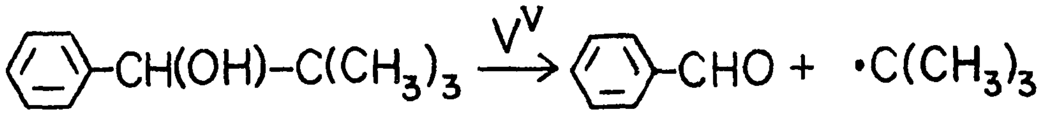
HISTORICAL

Oxidative Cleavage of Alcohols

Monohydric alcohols

There is much confusion in the literature over the role of cleavage in oxidative processes, especially in that of hydroxy compounds. Almost all of the common metal ion oxidants are known to cause C-C bond cleavage, at least in part, for appropriately substituted alcohols and glycols. In some cases, yields of cleavage products as high as 100% can be obtained. Often, cleavage is a serious side route causing low yields of a desired carbonyl product.

In those cases in which 100% cleavage of certain monohydric alcohols has been reported, all are by oxidants whose inorganic chemistry has shown them to be one-electron oxidants. Jones and Waters (8) reported that phenyl-*tert*-butylcarbinol was oxidized by vanadium(V), a one-electron oxidant, to give almost exclusively benzaldehyde and products derived from the *tert*-butyl fragment. Because of the one-electron nature of the oxidant, a free radical mechanism was proposed:



This same alcohol was reported by Mosher, Clement, and Hillard to undergo virtually total cleavage by cerium(IV), another one-electron oxidant, to give benzaldehyde and tert-butanol (6). A free radical mechanism has also been proposed in oxidative cleavage by cobalt(III), a powerful one-electron oxidant (9). In this case, tertiary alcohols have been shown to give cleavage products in similar ratios to those of cleavage of the corresponding alkoxy radicals.

It is in the oxidation of alcohols by those oxidants in which both one-electron and two-electron processes can take place that the confusion exists over the role of cleavage. Oxidation by chromic acid and lead tetraacetate are the two most notable examples.

In the case of chromic acid oxidations, both types of oxidation can take place because of the presence of the relatively unstable intermediate chromium oxidation states, chromium(V) and chromium(IV), in addition to the chromium(VI) ion. In 1944 Mosher and Whitmore (10) found that phenyl-tert-butylcarbinol gives products from a cleavage reaction as well as the normal pivalophenone. In 1956, Hampton, Leo, and Westheimer (11) established that one of the intermediate ions is responsible for cleavage by showing that manganous or cerous ions, which remove chromium(IV) as soon as it is formed, drastically reduced the extent of cleavage. By varying the conditions used, yields of cleavage products as high as 67% could be obtained. On the basis of this upper limit of cleavage product yields, the authors favored the mechanism in Scheme 1 in which chromium(V) is responsible for cleavage.

Cr(VI) + RCHOHR' → Cr(IV) + ketone
Cr(IV) + Cr(VI) → 2 Cr(V)
2 Cr(V) + 2 RCHOHR' → 2 Cr(III) + 2 RCHO + 2 R'OH

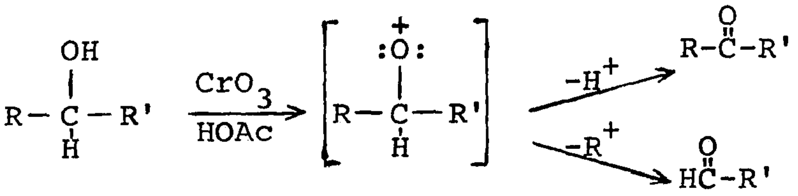
Scheme 1. Proposed mechanism showing chromium(V) giving rise to 67% cleavage ("Westheimer mechanism")

One should note that cleavage by this mechanism would be a two-electron process. They also presented the mechanism shown in Scheme 2 in which chromium(IV) would cause cleavage; however, they did not favor this mechanism since it would account for only 33% cleavage.

Cr(VI) + RCHOHR' → Cr(IV) + ketone
Cr(IV) + RCHOHR' → RCHO + R'· + Cr(III)
Cr(VI) + R'· + H_2O → Cr(V) + R'OH + H^+
Cr(V) + RCHOHR' → Cr(III) + ketone

Scheme 2. Proposed mechanism showing chromium(IV) giving rise to 33% cleavage

Earlier, Mosher and Whitmore had tentatively proposed an oxonium ion intermediate as presented in Scheme 3 to account for both cleavage and ketone formation.



Scheme 3. Oxonium ion mechanism of Mosher and Whitmore

As support of this mechanism, Mosher, Clement, and Hillard (6) in 1964 offered the evidence that when the R-group is varied as p-substituted phenyl groups, there is little change in the ratio of cleavage products to ketone. At the same time, these authors supported the Westheimer mechanism. How both of these mechanisms may be simultaneously satisfied is not made clear. The only argument against a free radical process is that isobutylene and 2,2,3,3-tetramethylbutane, expected from the tert-butyl radical, were not found. Waters has suggested, on the other hand, that since cleavage of this type is observed with vanadium(V), a one-electron process involving chromium(IV) and leading to a free radical is a strong possibility (12). Recently, Roček and Radkowsky have shown that it is possible in certain cases to experimentally distinguish between reactions of chromium(V) and chromium(IV) (7). They found that cyclobutanol is readily cleaved by chromium(IV), but is relatively unreactive toward chromium(V). Wiberg and Schäfer (13) have found by other methods that in many cases chromium(V) behaves very much like chromium(VI), and its oxidation of isopropanol to acetone is competitive with chromium(VI) oxidation. The Westheimer mechanism (Scheme 1) demands that the conversion of the alcohol to ketone by chromium(V) be a slow process compared with cleavage if yields approaching the maximum theoretical are to be obtained. Such a wide difference in products from the highly substituted alcohols by oxidation with chromium(V) as opposed to chromium(VI), both by two-electron processes, would not seem reasonable in light of the similarities mentioned. These recent findings suggest that chromium(IV), not chromium(V), is responsible for cleavage.

In the oxidative cleavage of tertiary alcohols by chromic acid, it was found by Sager (14) and Roček (15) that the rates are independent of the concentration of the oxidant, but correspond to the rates of acid catalyzed dehydration. Thus, it is the olefin which is oxidized by chromium(VI).

Oxidations by lead tetraacetate are complicated by the fact that lead(IV) itself can bring about both one-electron and two-electron oxidations. As in the case of chromic acid oxidations, lead tetraacetate can give rise to cleavage products as well as the normal carbonyl products; however, there is also a third route, namely the formation of cyclic ethers (16, 17). Heusler and Kalvoda favor a homolytic breakage of the lead-alkoxy bond (one-electron mechanism) to account for both cyclic ether formation and fragmentation.

These authors point out that hydrogen abstraction from the γ or δ carbon atom, which would be necessary to form a cyclic ether from an alcohol, is a common reaction of alkoxy radicals. Likewise, the fragmentation patterns follow those of alkoxy radicals. Mihailović and coworkers, who also favor an alkoxy-like intermediate, show that these reactions are favored in non-polar solvents, and that the ratio of cyclic ethers to cleavage products does not vary significantly with a change in polarity of the solvent. Finally, it has been found that cerium(IV) is also capable of converting an alcohol to a cyclic ether (4). These results suggest that cleavage by lead tetraacetate is by a one-electron oxidation. Mosher and coworkers, however, again favor an ionic mechanism (18). Methyl-tert-butylcarbinol was found by these workers to give 50% fragmentation products (acetaldehyde and tert-butylacetate) in acetic acid. The only evidence offered against a free radical mechanism is that no 2,2,3,3-tetramethylbutane nor isobutane was found. A similar alcohol, anisyl-tert-butylcarbinol was found by Norman and Watson to give extensive cleavage (19). These authors, too, favored a mechanism in which a tert-butyl cation is released; however, for the alcohol which has a benzyl group in place of the tert-butyl group, they favor a radical fragmentation. They found that cleavage of the alcohol with the tert-butyl group is faster than that of the alcohol with the benzyl group, which is the opposite of what one would expect if a free radical is ejected in both cases. In addition, coupling products, though present in small amounts, are formed from the benzyl fragment, whereas none are formed from the *tert*-butyl fragment. On the basis of these results, they propose a rather drastic change in mechanism upon changing the cleaved fragment from a *tert*-butyl group to a benzyl group.

Oxidation of secondary alcohols by permanganate can be controlled to give only ketones; however, some cleavage of alcohols such as phenyl-*tert*-butylcarbinol was reported for the oxidation in acetic acid (20). The reaction, however, was not studied in detail.

It should be pointed out that fragmentation reactions are quite common for alkoxy radicals but not for alkoxonium ions (21). The characteristic reaction of alkoxonium ions is, on the other hand, migration of a group to the electron deficient oxygen.

Diols

The cleavage of diols, particularly, 1,2-diols has been studied more extensively than that of monohydric alcohols, primarily because it occurs to a greater extent. The cleavage of diols is closely related to monohydric alcohol cleavage, and in some cases it might be just a simple alcohol cleavage giving a fragment which has a hydroxy group. There is the possibility of cyclic or bidentate intermediates for those diols whose geometry is favorable.[1] Whether there is a cyclic or a monodentate intermediate, there remains the question of whether the intermediate decomposes by a one-electron or a two-electron transfer to the metal.

The one-electron oxidants, vanadium(V), cerium(IV), and manganese(III) all cleave pinacol quantitatively (12). In each case there is evidence that the α-hydroxy radical is produced along with acetone.

In the oxidation of 1,2-diols by chromic acid, again, both cleavage products and carbonyl products are found. Pinacol is oxidized by chromic acid under conditions which have no effect on tert-butanol (22). Thus, it is clear that chromium(VI) itself is capable of causing cleavage in glycols. Walker has found, however, that in the oxidation of secondary-tertiary vicinal glycols, cleavage is drastically reduced by manganese(II) ions as in the case of monohydric alcohols (23). Walker attributes the cleavage to chromium(V) by analogy to the Westheimer mechanism for monohydric alcohols, but, as we have seen, it might well be attributed to chromium(IV). Apparently with chromium(VI), carbonyl formation is favored, but when this is not possible,

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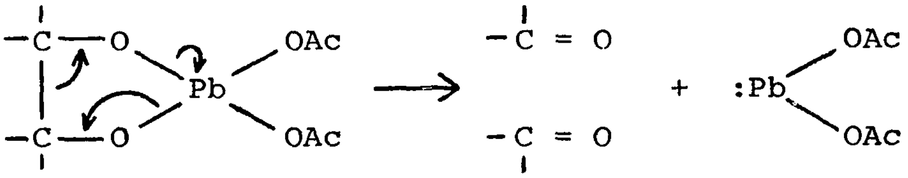
[1] This question has been discussed by Young and Trahanovsky (2).

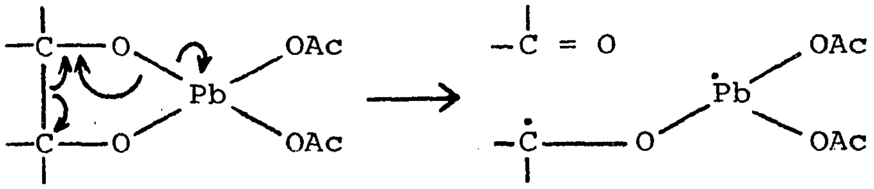
cleavage can occur. It is possible, then, that in glycols, other than ditertiary, chromic acid cleavage is a one-electron process leading to an α-hydroxy radical.

The well-known cleavage of glycols by lead tetraacetate is usually depicted as a heterolytic decomposition of a cyclic intermediate as first proposed by Criegee (24). This mechanism is outlined, in part, in Scheme 4.



Scheme 4. Two-electron transfer mechanism for lead tetraacetate oxidation of 1,2-glycols

It was found by workers in this group (25) that no trapping of an α-hydroxy radical by acrylamide took place for lead tetraacetate oxidation of a ditertiary glycol under conditions that gave virtually total trapping with cerium(IV) oxidation of the same glycol. These results were interpreted as indication that the lead tetraacetate cleavage of glycols is a two-electron oxidation; however, it was pointed out that there are two other ways to interpret the results. Oxidation of an intermediate radical might be faster by lead(IV) or lead(III) than by cerium(IV). Another possibility is that the radical may be complexed with lead making it unreactive with acrylamide. This might happen if, indeed, the reaction proceeds via the cyclic intermediate. A one-electron transfer such as that proposed for monohydric alcohols would in this case lead to a ketone and a lead(III) radical species as shown in Scheme 5.



Scheme 5. One-electron transfer mechanism for lead tetraacetate oxidation of 1,2-glycols

This lead(III) radical species could decompose with transfer of the second electron to give lead(II) and the ketone, and there would be no trappable free radical produced. Glycols are known to undergo cleavage with lead tetraacetate through a non-cyclic mechanism in cases such as trans-9,10-decalindiol where the cyclic ester would be impossible (26). In systems such as these it should be possible to determine definitely whether a homolytic or a heterolytic cleavage of the C-C bond is favored; however, such systems have not been studied in detail.

Stewart points out the fact that glycols are cleaved by permanganate at a rate slower than the oxidation of the corresponding alkenes (27), but that little detailed information is available on the reaction.

Oxidative Cleavage of Related Compounds

α-Hydroxy acids

α-Hydroxy acids are oxidized by vanadium(V), cerium(IV), and manganese(III) to form carbon dioxide and an α-hydroxy radical, whereas lead tetraacetate gives carbon dioxide and an aldehyde or a ketone (12). This is analogous to the case of 1,2-diols, and the same arguments may be used when considering them.

Chromic acid oxidation of α-hydroxy acids appears to lead to aldehydes with decarboxylation (28), although this reaction has not been studied in detail.

Stewart has found that benzilic acid is converted to benzophenone and carbon dioxide by acid permanganate (27). It was found that the lower oxidation states of manganese are much more effective oxidants for this reaction than permanganate itself.

Carboxylic acids

Carboxylic acids can undergo decarboxylation with some oxidants, but the rates are much slower than with the α-hydroxy acids just as the rates for oxidation of monohydric alcohols are slow in comparison with diols. Manganese(III) is not known to oxidize carboxylic acids but vanadium(V) can attack certain branched chain and unsaturated acids (29).

Kochi and Sheldon have shown that decarboxylation of cerium(IV) carboxylates proceeds by a free radical mechanism (30). Likewise cobalt(III) decarboxylation of acids leads to free radicals (29).

Chromic acid as chromium(VI) is rather unreactive toward carboxylic acids; however, Roček and Riehl (31) have found that decarboxylation of adipic acid can occur if the intermediate chromium ions are produced in solution by chromium(VI) oxidation of another substrate (induced oxidation). The final product is glutaric acid. Presumably, there is no effect of the second carboxyl group, and this would, therefore, be a general reaction of carboxylic acids. These authors attributed the decarboxylation to the chromium(V) species; however, using the arguments used for the alcohol cleavages, chromium(IV) decarboxylation might be more likely.

Lead(IV) carboxylates undergo thermal decarboxylation. Mosher and Kehr (32) proposed an ionic mechanism, again on the basis of a lack of coupling products. Kochi, Bacha, and Bethea have shown, however, that lead(IV) carboxylates decompose both thermally and photochemically by a free radical chain mechanism as outlined in Scheme 6 (33).

$$R\cdot + Pb^{IV}O_2CR \rightarrow R^+ + Pb^{III}O_2CR$$

$$Pb^{III}O_2CR \rightarrow Pb^{II} + CO_2 + R\cdot \quad \text{(etc.)}$$

Scheme 6. Radical chain mechanism for decarboxylation of lead(IV) carboxylates

Thus, decarboxylation for the most part is by lead(III).

Aldehydes

Wiberg and Richardson report that triphenylacetaldehyde is oxidized by chromic acid to give approximately one-third triphenylacetic acid and two-thirds cleavage to triphenylcarbinol and carbon monoxide (34). This is the same ratio of cleavage to normal oxidation as the maximum obtainable for secondary alcohol oxidation. The authors attributed the cleavage to chromium(V), but again chromium(IV) might be more likely. The authors point out that permanganate gives only the acid and cerium(IV) gives only cleavage. The oxidation probably proceeds through the hydrate form (35).

Oxidations of Alcohols by Cerium(IV)

Early studies of the oxidation of alcohols by cerium(IV) were reviewed by Richardson (36). Among the findings of these early studies was that oxidation proceeds through an alcohol-cerium(IV) complex which is in equilibrium with its components as shown in Equation 1. Complex formation for a large number of alcohols has been studied by Young and Trahanovsky (2).

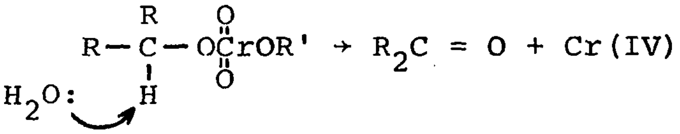
$$\mathrm{Ce^{IV}} + \mathrm{ROH} \underset{\text{fast}}{\rightleftarrows} \mathrm{(ROH)Ce^{IV}} \qquad (1)$$

$$\mathrm{(ROH)Ce^{IV}} \underset{\text{slow}}{\rightarrow} \mathrm{Ce^{III}} + \text{Products} \qquad (2)$$

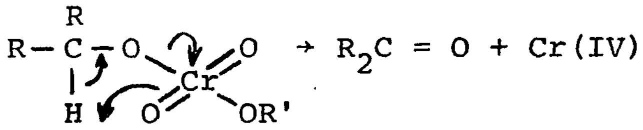
The complex will decompose with electron transfer to give cerium(III) and the products as in Equation 2. Such a mechanism has also been proposed for oxidations by vanadium(V) and cobalt(III) (12). In contrast to the similarities found for oxidative cleavage by vanadium(V), cerium(IV), cobalt(III), and manganese(III), a substantially greater hydrogen isotope effect is observed for vanadium(V) (k_H/k_D ca. 4) than for the other three oxidants (k_H/k_D,1.6-2.0). Waters attributes this difference to a transition state more like an α-hydroxy radical (C-H breakage) for vanadium(V) and one more like an alkoxy radical (O-H breakage) for the other three. The substituent effect on cerium(IV) oxidation of benzyl alcohol observed by Young (1) and the isotope effect, though small, demand some C-H bond breakage with charge development at the α-carbon.

Oxidations of Alcohols by Chromic Acid

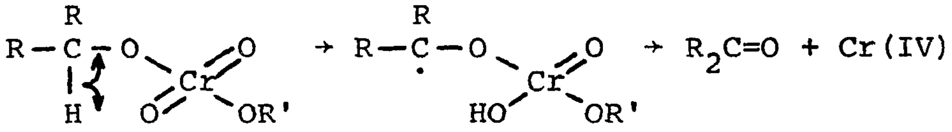
Wiberg and Schäfer have summarized the possible mechanisms for the oxidation of an alcohol to a carbonyl compound (13). Chromium(VI) mono- and diesters were shown to be intermediates. These esters can decompose in one of three ways as shown in Equations 3-5.



(3)



(4)



(5)

According to Wiberg and Schäfer, the favored mechanism is the one represented in Equation 4. For the next steps of the reaction, Roček and Radkowsky (7) favor the sequence in Equations 6-8.

$$R_2CHOH + Cr^{4+} \rightarrow R_2\dot{C}OH + Cr^{3+} \qquad (6)$$

$$R_2\dot{C}OH + Cr^{6+} \rightarrow R_2C = O + Cr^{5+} \qquad (7)$$

$$R_2CHOH + Cr^{5+} \rightarrow R_2C = O + Cr^{3+} \qquad (8)$$

Westheimer and Watanabe (37), however, favor the disproportionation reaction (Equations 9 and 10).

$$Cr^{4+} + Cr^{6+} \rightleftarrows 2\ Cr^{5+} \qquad (9)$$

$$2(R_2CHOH + Cr^{5+} \rightarrow R_2C = O + Cr^{3+}) \qquad (10)$$

All evidence at present is compatible with either sequence.

Wiberg and Schäfer have found evidence that the oxidation of an alcohol by chromium(V) also proceeds through an ester intermediate (13).

Oxidative cleavage by chromium(VI) was discussed in the section on oxidative cleavages.

RESULTS AND DISCUSSION

General Considerations

If we consider the oxidation of an alcohol by a metal ion to proceed via a complex, as evidence indicates for both cerium(IV) (2) and chromic acid (13), the competitive oxidation of two alcohols, A_1 and A_2, may be represented as in Equations 11 and 12, where M is the oxidizing species, X_1 and X_2

$$A_1 + M \overset{K_1}{\rightleftarrows} X_1 \overset{k_1}{\rightarrow} P_1 \qquad (11)$$

$$A_2 + M \overset{K_2}{\rightleftarrows} X_2 \overset{k_2}{\rightarrow} P_2 \qquad (12)$$

the complexes, and P_1 and P_2 the products. The following derivation gives an expression for the relative rates of oxidation.

$$K_1 = \frac{[X_1]}{[M][A_1]}$$

The concentration of free alcohol may be expressed as $[A_1]_T - [X_1]$, where $[A_1]_T$ = total A_1.

$$K_1 = \frac{[X_1]}{[M]([A_1]_T - [X_1])}$$

$$\frac{d[P_1]}{dt} = \frac{-d[A_1]}{dt} = k_1[X_1] = k_1\left(\frac{K_1[M][A_1]_T}{1+K_1[M]}\right) \qquad (13)$$

Similarly,

$$\frac{d[P_2]}{dt} = \frac{-d[A_2]}{dt} = k_2[X_2] = k_2(\frac{K_2[M][A_2]_T}{1+K_2[M]}) \qquad (14)$$

Dividing Equation 13 by Equation 14 we obtain

$$\frac{d[A_1]}{d[A_2]} = \frac{k_1(\frac{K_1[M][A_1]_T}{1+K_1[M]})}{k_2(\frac{K_2[M][A_2]_T}{1+K_2[M]})}$$

Rearranging,

$$\frac{d[A_1]}{d[A_2]} = (\frac{k_1}{k_2})(\frac{[A_1]_T}{[A_2]_T})(\frac{K_1}{K_2})(\frac{1+K_2[M]}{1+K_1[M]}) \qquad (15)$$

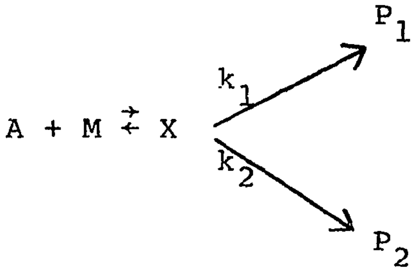
Upon inspection of Equation 15, it can be seen that if $K_1 = K_2$, the last two terms drop out the relative rates may be expressed as in Equation 16.

$$\frac{k_1}{k_2} = \frac{(1/[A_1]_T)d[A_1]}{(1/[A_2]_T)d[A_2]} \qquad (16)$$

The ratio k_1/k_2 represents the substituent effect on complex decomposition and thus upon fragmentation. Competition studies depend, then, upon the validity of the assumption, $K_1 = K_2$. The effect of a substituent of the 2-phenyl ring might be expected to have little effect on the equilibrium constant of complex formation. Indeed, it has been found by workers in this research group (2) that in cerium(IV) complex formation with substituted benzyl alcohols, where the substituent is even one carbon atom closer to the reaction center, the equilibrium constant ranges only from 0.64 for *p*-nitrobenzyl alcohol to 0.82 for *p*-methylbenzyl alcohol.

Since the assumption, $K_1 = K_2$, is probably valid for this series, the most serious question about using Equation 16 to determine k_1/k_2 is whether or not an equilibrium situation exists for complex formation. If this were not the case, the values for relative rates as calculated by Equation 16 would reflect, to some extent, the first step. Since the substituent effect of this step would be smaller than that for the second step, the result would be that the calculated ρ value would be too small.

Because of this uncertainty of the effect of complex formation, the system 1-aryl-2,3-diphenylpropan-2-ol was studied. This system may be represented, using the same symbols as before, as follows:



$$\frac{d[P_1]}{dt} = k_1[X]$$

$$\frac{d[P_2]}{dt} = k_2[X]$$

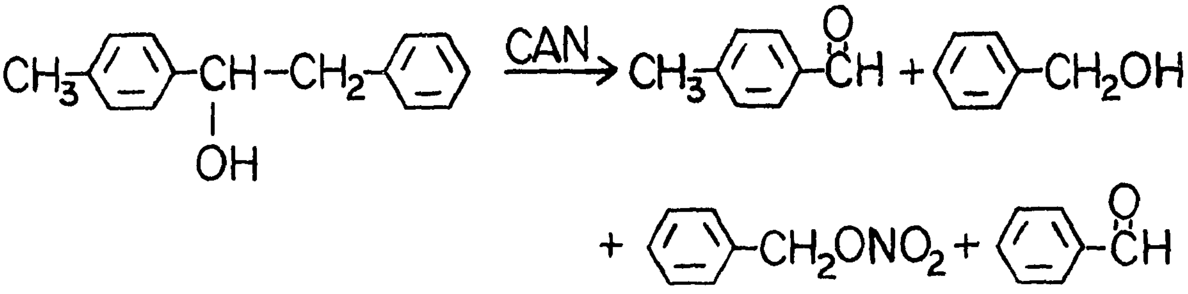
$$\frac{d[P_1]}{d[P_2]} = \frac{k_1}{k_2}$$

Thus, in this internal competition, k_1/k_2 is measured simply by the product ratio and the complexation step has no effect.

Comparison of both these systems reveals information about the complexation step of oxidations by both cerium(IV) and chromium(VI).

Product identification

For the initial product study of the ceric ammonium nitrate (CAN) oxidations of 1,2-diarylethanols, 1-p-tolyl-2-phenylethanol was chosen in order that products from the two moieties could be distinguished. Products were determined by glpc peak enhancement and nmr analysis. The reaction is represented in Equation 17.



(17)

It will be shown later that if this reaction had been run under nitrogen, no benzaldehyde would have been produced. None of the corresponding ketone was found either by glpc or by nmr analysis; thus, the oxidation gives exclusively cleavage products. That the ketone could not have been a transient intermediate was shown by the fact that the oxidation of deoxybenzoin was very slow and gave a large amount of a product which (by glpc analysis) was not found in the oxidation of 1,2-diphenylethanol. This glpc peak was enhanced by benzil, but no other attempts to identify the product were made.

Radical trapping experiments

In order to help establish that cleavage by cerium(IV) is a one-electron oxidation leading to a radical fragment, the oxidation of 1-*p*-tolyl-2-phenylethanol was carried out in the presence of known radical traps, acrylamide and oxygen. The products of these reactions were analyzed by nmr. The relative ratios of the product peaks are recorded in Table 1. It is seen that in the presence of acrylamide, the yield of products from the benzyl moiety is significantly reduced relative to the *p*-tolualdehyde produced. Oxygen was found to be a more effective trap. No benzyl nitrate was found, but benzaldehyde and a small amount of benzyl alcohol were recovered. Both of these products could be

Table 1. Relative ratios of nmr peaks for trapping experiments in the oxidation of 1-p-tolyl-2-phenylethanol by CAN

Additive	Tolualdehyde	Benzaldehyde	Benzyl nitrate	Benzyl alcohol
None	10.0	-	17.7	3.1
Acrylamide (5g)	10.0	-	11.5	2.9
Acrylamide (25g)	10.0	-	10.7	2.5
Oxygen (1 atm)	10.0	10.0	-	2.6

expected as decomposition products of the benzyl peroxy radical (38).

Competitive oxidations of 2-aryl-1-phenylethanols

Oxidations in 75% acetonitrile

It was shown in the section, General Considerations, that if one assumes that for 1,2-diphenylethanol there is negligible effect on the equilibrium constant for complex formation of a substituent on the 2-phenyl ring, the ratio of rate constants for two such alcohols in competition is measured simply by the change in concentration of each alcohol (Equation 16).

$$\frac{k_1}{k_2} = \frac{(1/[A_1])d[A_1]}{(1/[A_2])d[A_2]} \qquad (16)$$

Upon integration between the limits initial, o, and final, f, concentration one obtains

$$\frac{k_1}{k_2} = \frac{\ln[A_1]o - \ln[A_1]_f}{\ln[A_2]o - \ln[A_2]_f} \qquad (18)$$

The values obtained for the ratios k_1/k_2 for the competitive oxidations by CAN in acetonitrile are shown in Table 2. The unsubstituted alcohol is taken as A_2, and thus the rate ratios are labelled as k/k_H.

Table 2. Relative rates of oxidation of 2-aryl-1-phenylethanols by CAN in 75% acetonitrile

Alcohol	k/k_H	$\log(k/k_H)$
p-CH_3	4.2	0.62 ± .04
H	(1.00)	(0.00)
p-Cl	0.63	-0.20 ± .04
p-NO_2	0.028	-1.55 ± .20
p-CH_3O	>100[a]	>2[a]
m-CH_3O	>100[a]	>2[a]
p-AcNH	>100[a]	>2[a]

[a] Estimated.

It is seen that the alcohols with the substituents *p*-CH_3O, *m*-CH_3O, and *p*-AcNH were oxidized so much faster than the parent, that the relative rates could not be accurately measured by the methods used. From a rough estimate, based on the accuracy of the measurement, it appears that all three are oxidized at a rate greater than one-hundred times faster than the parent.

For those alcohols on which accurate measurements could be made, the values of $\log(k/k_H)$ (Table 1) were plotted against their σ^+ constants (Table 3). This plot appears in Figure 1.

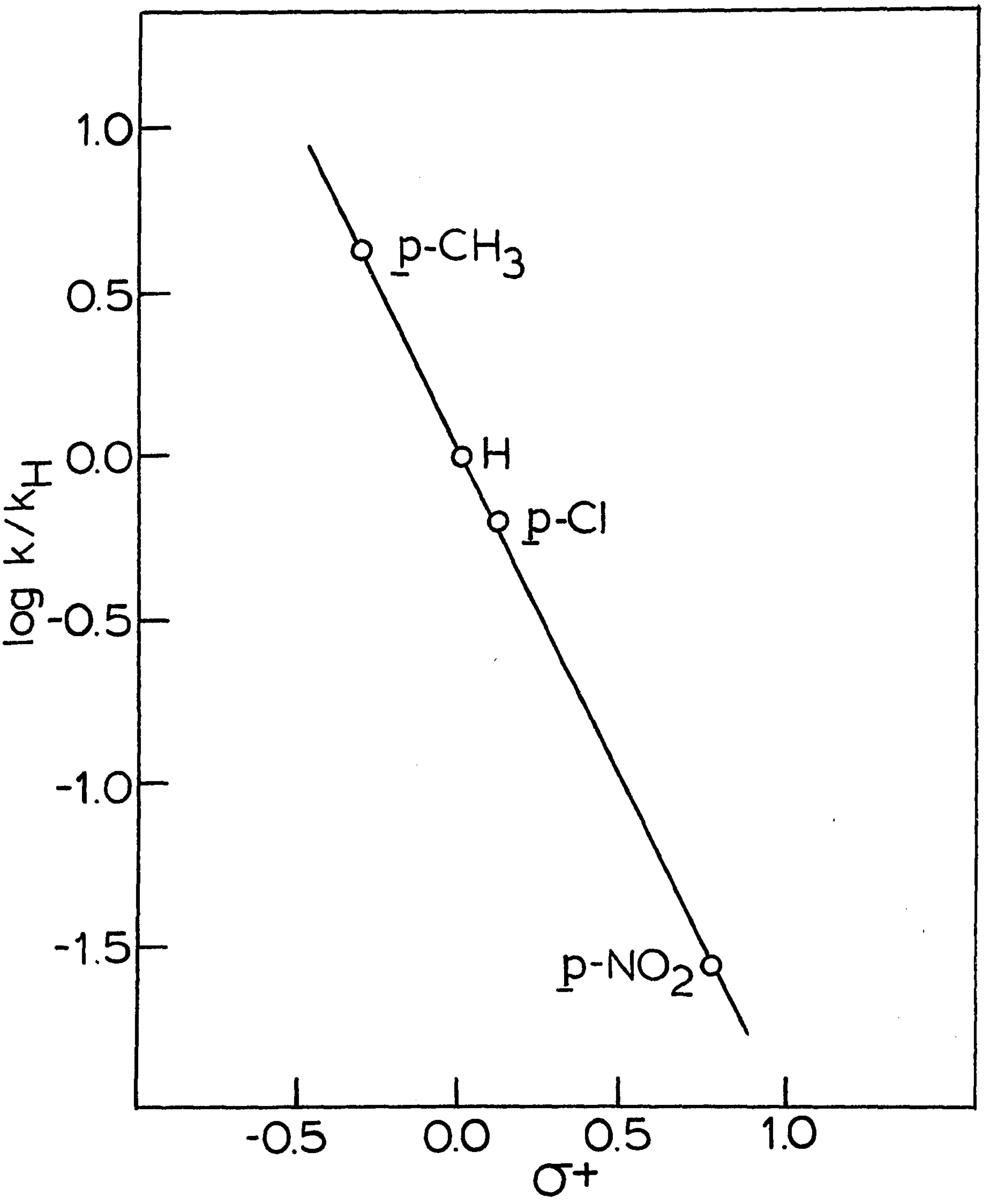
Table 3. Hammett σ and σ^+ constants[a]

Substituent	σ	σ^+
p-CH_3	-0.170	-0.311
p-Cl	0.227	0.114
p-NO_2	0.778	0.790
p-CH_3O		-0.778
m-CH_3O		0.047
p-AcNH		-0.6

[a] Values obtained from reference (39).

It is evident that the data for the alcohols with substituents p-CH_3O, m-CH_3O, and p-AcNH would not fit on the plot. Taken alone, the data for the p-methoxy and p-acetylamino alcohols might indicate that the unusually rapid rates are due to the ability of these two substituents to stabilize positive charge at the benzylic carbon. The experiment with the m-methoxy alcohol shows that this is not the case. The σ^+ value for a m-methoxy group is positive

Figure 1. Hammett plot (σ^+) for CAN oxidation of 2-aryl-1-phenylethanols in 75% aqueous acetonitrile


1.0
0.5
0.0
-0.5
-1.0
-1.5
log k/k$_H$
p-CH$_3$
H
p-Cl
p-NO$_2$
-0.5
0.0
0.5
1.0
σ+

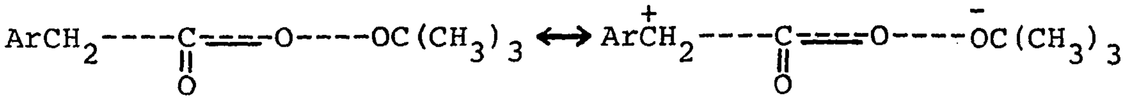
and therefore has a destabilizing effect on a cation at the benzylic position. The fact that the oxidation of this alcohol is also very fast suggests that the unusual effect of these groups is associated with oxidation of the groups or attack on the aromatic ring. Duffin and Tucker have reported that in the chromic acid oxidation of several substituted toluenes, the methoxy group could not be studied because it facilitates attack of the aromatic nucleus (40). One possibility for the mode of attack of the aromatic ring is an electron-transfer oxidation to give a radical cation. Such a process was proposed by Andrulis and coworkers for manganese(III) oxidation of p-methoxytoluene (41) and by Allara and coworkers (42) for lead tetraacetate-boron trifluoride oxidation of anisole and N,N-dimethylaniline.

The ρ value calculated from the Hammett plot (Figure 1) was -2.0 (-2.00 ± .02). While this value is slightly higher than most processes leading to benzyl radicals, -0.7 to -1.5 (43, 44, 45, 46, 47), it is closer to these values than to those for processes leading to benzyl cations, -4.5 to -6.7 (39, 48, 49, 50, 51). Abstractions of a benzylic hydrogen from substituted toluenes (44, 45, 46, 47) have been found to correlate best with σ^+ values in all cases except abstractions by the tert-butoxy radical (46, 47). Correlation by σ^+ values is thought to reflect benzylic cation character in the transition state as in resonance form B.

$$\mathrm{ArCH_2{-}{-}{-}{-}H{-}{-}{-}{-}X} \longleftrightarrow \mathrm{Ar\overset{+}{C}H_2{-}{-}{-}{-}H{-}{-}{-}{-}\overset{-}{X}}$$

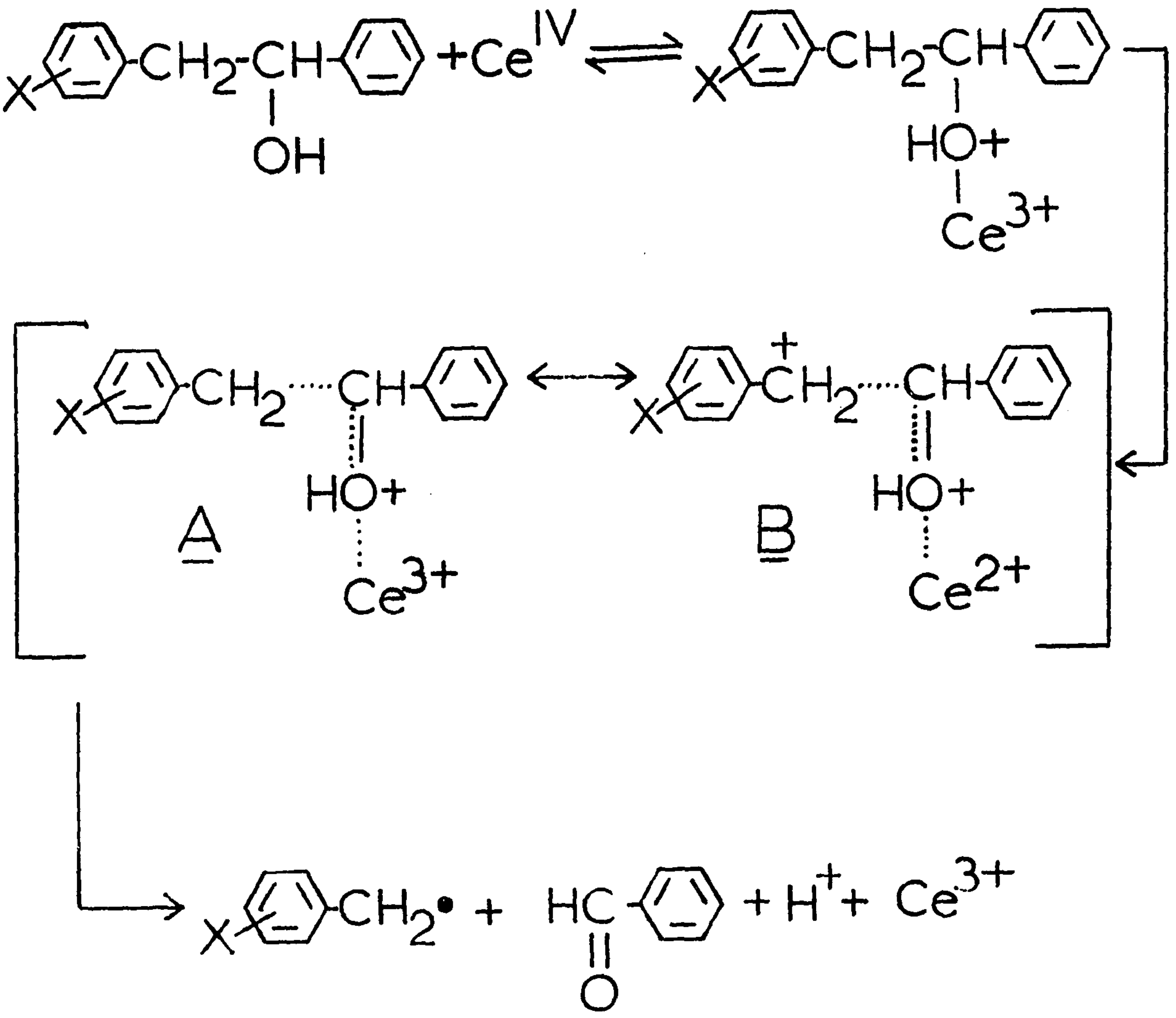
$\underline{\mathrm{A}}$ $\underline{\mathrm{B}}$

Bartlett and Rüchardt likewise found better correlation with σ^+ than with σ in the thermolysis of *tert*-butyl phenylperacetates (43). A transition state analogous to the one above was proposed.



$$\mathrm{ArCH_2{-}{-}{-}{-}\underset{\underset{\displaystyle O}{\|}}{C}{=}{=}{=}O{-}{-}{-}{-}OC(CH_3)_3} \longleftrightarrow \mathrm{Ar\overset{+}{C}H_2{-}{-}{-}{-}\underset{\underset{\displaystyle O}{\|}}{C}{=}{=}{=}O{-}{-}{-}{-}\overset{-}{O}C(CH_3)_3}$$

The Hammett plot using σ values for the oxidative cleavage by cerium(IV) is not shown; however, because of the very good correlation using σ^+ values, it is safe to say that the latter gives the better correlation. A transition state analogous to those proposed for hydrogen abstraction and perester thermolysis may be proposed for cerium(IV) cleavage of alcohols. The proposed mechanism is shown in Scheme 7. For simplicity the other ligands on the ceric ion are not shown. The oxidation clearly does not involve a free alkoxy radical as an intermediate for there must be considerable stretch of the C-C bond in the transition state of the slow step. The larger negative ρ value for this system over other radical processes might be due to the role of the positively charged metal ion as reflected in resonance form $\underline{\mathrm{B}}$. This is not unreasonable since a transition state in which



Scheme 7. Proposed mechanism for oxidative cleavage of 2-aryl-1-phenylethanols by cerium(IV)

the charge of the metal ion is more spread out should be favorable. Thus, the unusual nature of this leaving group, which contains a highly charged metal ion, might well be expected to lead to a higher ρ value than is found for other processes leading to free radicals, although this might not always be true.

Oxidation in 85% acetic acid Acetonitrile was used for the initial competition studies because it had often proved to be the most convenient solvent for CAN oxidations. When it was decided to extend the work to chromic acid, which is unstable in acetonitrile solutions, it seemed worthwhile to repeat the studies, at least in part, in acetic acid solution. Only the alcohols with the substituents $\underline{p}$-CH_3, $\underline{p}$-H, and $\underline{p}$-Cl were studied because of difficulties encountered previously with measurements of the $\underline{p}$-NO_2 alcohol competitions. The values of k/k_H and $\log(k/k_H)$ for the competitive oxidations in 85% acetic acid are recorded in Table 4.

Table 4. Relative rates of oxidation of 2-aryl-1-phenylethanols by CAN in 85% acetic acid

Alcohol	k/k_H	$\log(k/k_H)$
$\underline{p}$-CH_3	4.1	0.61 ± .02
H	(1.00)	(0.00)
$\underline{p}$-Cl	0.57	-0.245 ± .004

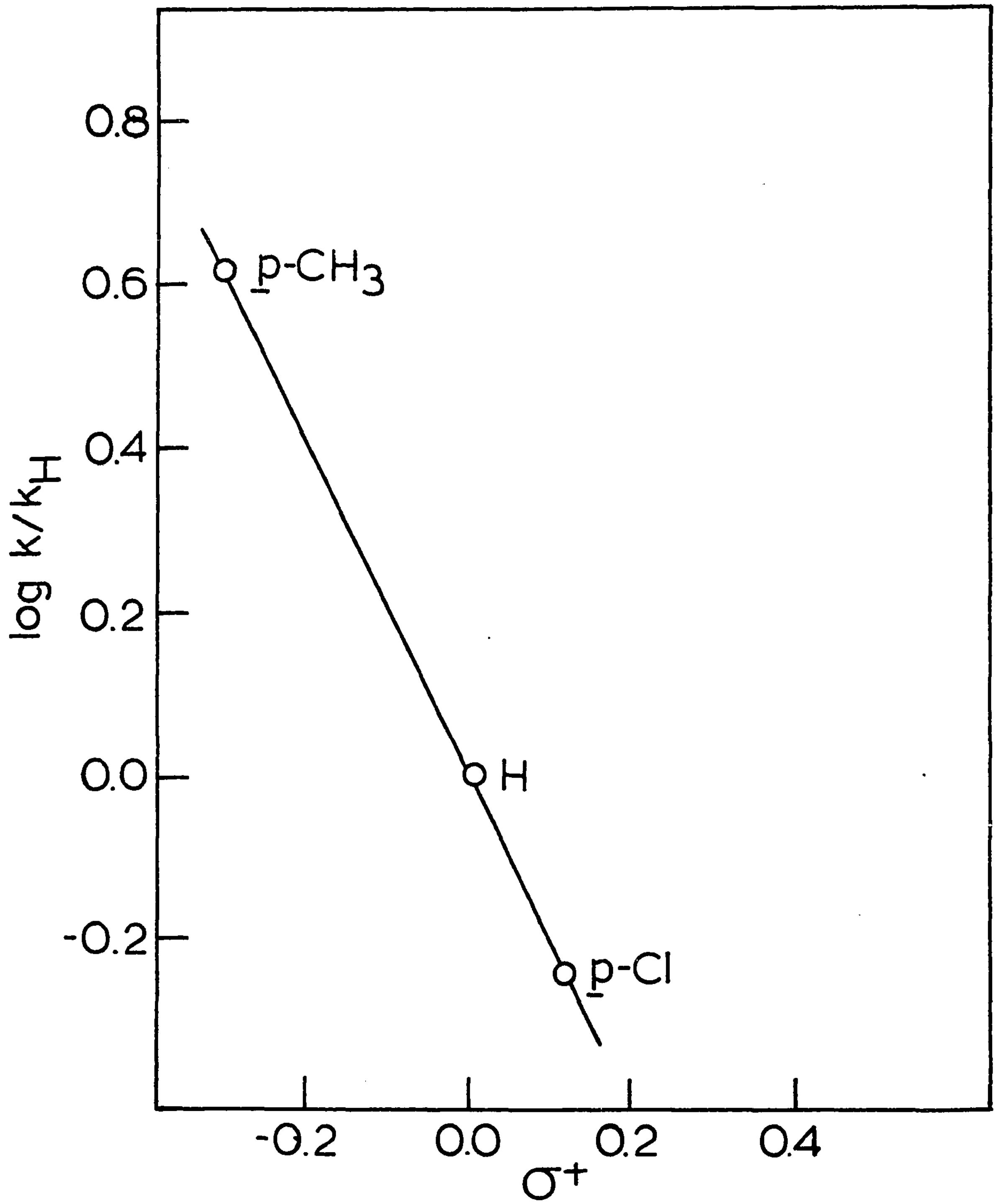
The Hammett plot of $\log(k/k_H)$ using σ^+ values appears in Figure 2. The ρ value for this plot was again -2.0 (-2.01 ± .04). Thus there was no change in the ρ value with this change in solvent.

Oxidation of 1,2-Diarylethanols by Chromic Acid

Product studies

Unlike the simple case of ceric ion oxidations where only cleavage products are obtained, chromic acid oxidation gives both cleavage products and ketone. The nmr spectrum of the product mixture of the oxidation of 2.4 mmoles of 1,2-diphenylethanol in 85% acetic acid showed a ratio of benzaldehyde (9.83δ) to deoxybenzoin (methylene protons at 4.15δ) of 2:3. No other products were observed. Benzyl alcohol was expected from the fragment by analogy with the work of Mosher and coworkers (6), but apparently further oxidation to benzaldehyde is so fast under these conditions it cannot be recovered. To prove this, the experiment was repeated with the addition of 1.2 mmoles of p-chlorobenzyl alcohol. Oxidation of the substituted benzyl alcohol to the aldehyde was so rapid that very little oxidation of 1,2-diphenylethanol took place. It will be shown later that upon making the reaction mixture 0.5 M in sodium acetate, the rate of further oxidation of benzyl alcohol is retarded to such an extent that it can, in part, be recovered. The

Figure 2. Hammett plot (σ^+) for CAN oxidation of 2-aryl-1-phenylethanols in 85% aqueous acetic acid


log k/k_H
0.8
0.6
0.4
0.2
0.0
-0.2
p-CH3
H
p-Cl
-0.2
0.0
0.2
0.4
σ+

oxidative cleavage of one molecule of 1,2-diphenylethanol, then, under normal conditions leads ultimately to two molecules of benzaldehyde. The ratio of benzaldehyde to ketone calculated from the relative peak areas corresponds to *ca.* 25% cleavage. It was found that the percent cleavage was increased to *ca.* 50% by the addition of sodium acetate (0.1 *M*). This effect of sodium acetate has been observed by Mosher and coworkers (6) and by Hampton, Leo, and Westheimer (11).

Attempted radical trapping with acrylamide and acrylonitrile

In order to help determine whether or not the chromic acid cleavage of an alcohol leads to a radical fragment, 1,2-diphenylethanol was oxidized in an 85% acetic acid solution containing acrylamide or acrylonitrile. In neither case was there any precipitate formed. This is in contrast with the previous work with cerium(IV) using acrylamide and with Mosher's work with chromic acid using acrylonitrile (6). In the nmr spectra of the product mixtures, comparison with the run without the radical trap showed that there was no change in the ratio of benzaldehyde to starting material when the trap is used.

These experiments show that either no radical is formed or that further oxidation of a radical by a metal ion is very rapid and thus competes with trapping by acrylamide or acrylonitrile. The trapping experiments with oxygen below support the latter explanation. Wiberg and Ford have encountered similar difficulties in the attempted trapping of benzoyl radicals generated in the oxidation of benzaldehyde (52).

Radical trapping with oxygen

In Table 5a is listed the data obtained for the oxidation of 1,2-diphenylethanol under nitrogen and under oxygen. The extraction ratios of 1,2-diphenylethanol and deoxybenzoin obtained for the competition studies were used to calculate the amount of these compounds present after the reactions. A crude extraction ratio was obtained for benzyl alcohol but with only one run. This value was found to be 0.7.

Table 5a. Effect of oxygen on the oxidation of 1,2-diphenylethanol in 85% acetic acid

Compound	Peak Areas		mmoles	
	N_2	O_2	N_2	O_2
1,2-Diphenylethanol	86.7	68.0	0.623	0.447
Deoxybenzoin	47.8	82.7	.331	.524
Benzyl alcohol	28.9	-	.303	-
Standard	54.5	51.0		

The amount of cleavage for the run under N_2 calculated by $[A]_o-[A]_f-[Kt]$, where $[A]_o$ and $[A]_f$ are initial and final quantities of the alcohol and [Kt] is the quantity of ketone formed, is equal to 0.646 mmoles. Thus the ratio of remaining benzyl alcohol to cleavage is approximately 50%. It is assumed that all of the benzyl fragment forms benzyl alcohol and that the reason only 50% is found is because of further oxidation to benzaldehyde as shown previously. In the reaction under oxygen, benzyl alcohol is eliminated as a product. In the control experiment in which oxygen was bubbled through a heated chromium(III) solution containing benzyl alcohol, no oxidation by oxygen to benzaldehyde was observed. This can only mean that in the fragmentation experiment under oxygen, benzyl alcohol is not formed at all. It would appear from the data that in the reaction under oxygen, the ratio of ketone formation to cleavage is larger than in the reaction under nitrogen; however, when we take into account the oxidation of benzyl alcohol to benzaldehyde in the nitrogen experiment, there is little difference in the ratio of total carbonyl formation to cleavage. In the oxidation of 1-p-tolyl-2-phenylethanol using somewhat different conditions the peak for benzyl alcohol was greatly diminished with oxygen, although a trace remained. In this case both benzaldehyde and p-tolualdehyde were produced, and the ratio of the peak heights of benzaldehyde:p-tolualdehyde increased from 0.55 for the run under nitrogen to 0.80 for the run under oxygen. Thus, as in the case of oxygen trapping in the CAN oxidation, the benzyl radical is converted directly to benzaldehyde.

Competitive oxidations of 2-aryl-1-phenylethanol

For the competition of two alcohols in chromic acid oxidation, the reactions which take place may be represented as follows:

$$A_1 + Cr^{+n} \overset{K_{11}}{\rightleftarrows} X_{11} \xrightarrow{k'_{11}} Kt_1$$

$$A_1 + Cr^{+n'} \overset{K_{12}}{\rightleftarrows} X_{12} \xrightarrow{k'_{12}} CP_1$$

$$A_2 + Cr^{+n} \overset{K_{21}}{\rightleftarrows} X_{21} \xrightarrow{k'_{21}} Kt_2$$

$$A_2 + Cr^{+n'} \overset{K_{22}}{\rightleftarrows} X_{22} \xrightarrow{k'_{22}} CP_2$$

where A_1 and A_2 are the alcohols, Kt_1 and Kt_2 the ketones, and CP_1 and CP_2 the cleavage products. The X terms represent the alcohol-chromium complexes. As mentioned previously, n=6 and n'= either 4 or 5. In order to determine the substituent effect upon the cleavage reaction, the ratio k'_{12}/k'_{22} must be calculated. It would also be of interest to know the substituent effect upon ketone formation, k'_{11}/k'_{21}. As in the more simple case shown in the section, General Considerations, if $K_{11} = K_{21}$ and $K_{12} = K_{22}$, the terms involving these equilibrium constants are cancelled in the expressions for the above ratios. These expressions are the same as those which are obtained if the reactions are represented in the following manner:

$$A_1 + Cr^{+n} \xrightarrow{k_{11}} Kt_1$$

$$A_1 + Cr^{+n'} \xrightarrow{k_{12}} CP_1$$

$$A_2 + Cr^{+n} \xrightarrow{k_{21}} Kt_2$$

$$A_2 + Cr^{+n'} \xrightarrow{k_{22}} CP_2$$

These rate constants involve both the equilibrium constants for complex formation and the rate constants of complex decomposition. If $K_{11} = K_{21}$ then $k_{11}/k_{21} = k'_{11}/k'_{21}$; similarly, if $K_{12} = K_{22}$, $k_{12}/k_{22} = k'_{12}/k'_{22}$. The following derivation, using these assumptions, gives the expressions for the relative rates of cleavage and ketone formation.

$$\frac{-d[A_1]}{dt} = [A_1]k_{11} + [A_1]k_{12} = [A_1](k_{11} + k_{12})$$

$$\frac{-d[A_2]}{dt} = [A_2]k_{21} + [A_2]k_{22} = [A_2](k_{21} + k_{22})$$

$$\frac{d[A_1]}{d[A_2]} = \frac{(k_{11} + k_{12})[A_1]}{(k_{21} + k_{22})[A_2]}$$

$$\frac{(k_{11} + k_{12})}{(k_{21} + k_{22})} = \frac{(1/[A_1])d[A_1]}{(1/[A_2])d[A_2]} \qquad (19)$$

Integrating between the limits of initial, o, and final, f, concentration, we obtain

$$\frac{(k_{11} + k_{12})}{(k_{21} + k_{22})} = \frac{\ln([A_1]_o/[A_1]_f)}{\ln([A_2]_o/[A_2]_f)} = K_L \tag{20}$$

Since this quantity is a constant, it is represented as K_L. In order to obtain k_{12}/k_{22} we must know for each alcohol, A_X, the ratio k_{X1}/k_{X2}, which is the ratio of ketone formation to cleavage. These ratios are not necessarily equal to the k'_{X1}/k'_{X2} ratios; however, again, the factors introduced by considering the differences in equilibrium constants are cancelled in the final expression for k_{11}/k_{21} and k_{12}/k_{22}.

$$\frac{d[Kt_1]}{dt} = [A_1]k_{11}$$

$$\frac{d[CP_1]}{dt} = [A_1]k_{12}$$

$$\frac{d[Kt_1]}{d[CP_1]} = \frac{k_{11}}{k_{12}}$$

Integrating, we obtain

$$\frac{k_{11}}{k_{12}} = \frac{[Kt_1]}{[CP_1]}$$

Similarly,

$$\frac{k_{21}}{k_{22}} = \frac{[Kt_2]}{[CP_2]}$$

$$K_L = \frac{(k_{11} + k_{12})}{(k_{21} + k_{22})} = \frac{(k_{11}/k_{12}) + (k_{12}/k_{12})}{(k_{21}/k_{12}) + (k_{22}/k_{12})}$$

$$K_L = \frac{(\frac{[Kt_1]}{[CP_1]} + 1)}{(k_{21}/k_{12}) + (k_{22}/k_{12})}$$

Rearranging gives

$$\frac{K_L}{(\frac{[Kt_1]}{[CP_1]} + 1)} = \frac{k_{12}}{(k_{21} + k_{22})} \tag{21}$$

$$\frac{k_{12}}{(k_{21} + k_{22})} = \frac{k_{12}/k_{22}}{(k_{21}/k_{22}) + (k_{22}/k_{22})} = \frac{k_{12}/k_{22}}{(\frac{[Kt_2]}{[CP_2]} + 1)} \tag{22}$$

Combining Equations 21 and 22 are rearranging gives

$$\frac{k_{12}}{k_{22}} = K_L \frac{(\frac{[Kt_2]}{[CP_2]} + 1)}{(\frac{[Kt_1]}{[CP_1]} + 1)} = K_L \frac{(\frac{[Kt_2]+[CP_2]}{[CP_2]})}{(\frac{[Kt_1]+[CP_1]}{[CP_1]})}$$

Rearranging and substituting the expression K_L in Equation 20 gives

$$\frac{k_{12}}{k_{22}} = \frac{\log([A_1]_o/[A_1]_f)}{\log([A_2]_o/[A_2]_f)} \cdot \frac{\left(\frac{[CP_1]}{[Kt_1]+[CP_1]}\right)}{\left(\frac{[CP_2]}{[Kt_2]+[CP_2]}\right)} \tag{23}$$

The equation for the relative rates of ketone formation is derived similarly (Equation 24).

$$\frac{k_{11}}{k_{21}} = \frac{\log([A_1]_o/[A_1]_f)}{\log([A_2]_o/[A_2]_f)} \cdot \frac{\left(\frac{[Kt_1]}{[Kt_1]+[CP_1]}\right)}{\left(\frac{[Kt_2]}{[Kt_2]+[CP_2]}\right)} \tag{24}$$

The quantities CP_1 and CP_2 were calculated as

$$[CP_1] = [A_1]_o - [A_1]_f - [Kt_1]$$

$$[CP_2] = [A_2]_o - [A_2]_f - [Kt_2]$$

Thus, the relative rates of cleavage and of ketone formation may be determined by knowing the initial and final concentration of each alcohol and the final concentration of ketone. Since the volume is a constant, the ratio of concentrations is measured by the number of mmoles of each compound.

The data obtained was used to calculate the values for k_{11}/k_{21} and k_{12}/k_{22} for each competition experiment. These values are recorded in Table 5b. In Table 6a the average values of the rates of cleavage and ketone formation relative to the parent alcohol are presented. The rates of the p-chloro relative to the parent were obtained by multiplying k_{Cl}/k_{NO_2} by k_{NO_2}/k_H. The one experiment which measured these values directly serves a check for the overall method. The values for the logs of the averages are also recorded in Table 6a.

In the competition p-Cl vs. p-NO_2 alcohol, the nmr analysis method used was the one in which one peak of the doublet for each alcohol was measured and multiplied by the appropriate factor to account for the other peak. In the competition p-Cl vs. p-H, the method used was the one in which the peaks were expanded and the area measured by planimetry. In this case both peaks of each alcohol could be measured. The close agreement, 0.65 ± .05 compared with 0.70 for cleavage and 0.93 ± .07 compared with 1.03 for ketone formation not only speaks well for these methods of analysis, but also checks the values of the p-NO_2 ratios since these were used to calculate the p-Cl ratios in the indirect method. The values of log k/k_H for both processes were plotted against the respective σ and σ^+ values from Table 3. The Hammett σ plots appear in Figure 3 and the σ^+ plots in Figure 4. For cleavage, the ρ values are -1.06 ± 0.04 using σ constants and -0.96 ± 0.07 using σ^+ constants. For ketone formation the ρ values are -0.10 ± 0.02 using σ

Table 5b. Relative rates of cleavage and ketone formation in chromic acid oxidations of 2-aryl-1-phenylethanols

Alcohols Competing		Cleavage Ratios	Ketone Ratios
A_1	A_2	(k_{12}/k_{22})	(k_{11}/k_{21})
p-CH$_3$	*p*-H	1.62	0.99
		1.60	.95
		1.50	1.00
p-NO$_2$	*p*-H	0.16	.85
		0.13	.75
		0.17	.81
p-Cl	*p*-NO$_2$	4.11	1.16
		4.42	1.22
		4.60	1.13
p-Cl	*p*-H	0.70	1.03

Table 6a. Average rates of cleavage and ketone formation of 2-aryl-1-phenylethanols relative to the parent alcohol

Alcohol	k/k_H Cleavage	$\log(k/k_H)$ Cleavage	k/k_H Ketone formation	$\log(k/k_H)$ Ketone formation
p-H	(1.00)	(0)	(1.00)	(0)
p-CH$_3$	1.57±.05	0.20±.01	0.98±.02	-0.01±.01
p-Cl	.65±.05	-0.18±.04	.93±.07	-0.03±.03
p-NO$_2$	.15±.02	-0.82±.04	.80±.04	-0.10±.02

Figure 3. Hammett plots (σ) for cleavage (o) and ketone formation (Δ) in the chromic acid oxidation of 2-aryl-1-phenylethanols

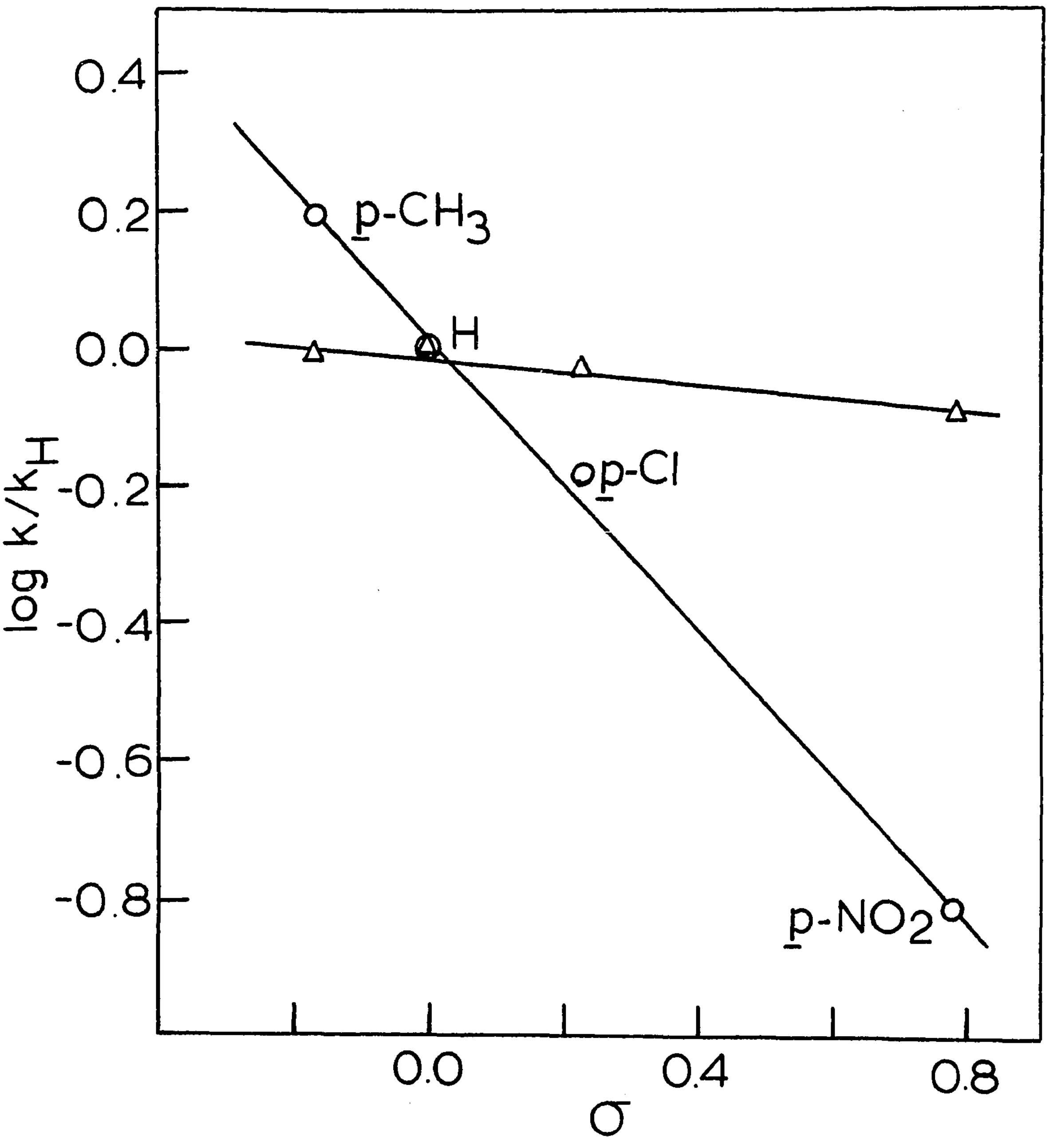
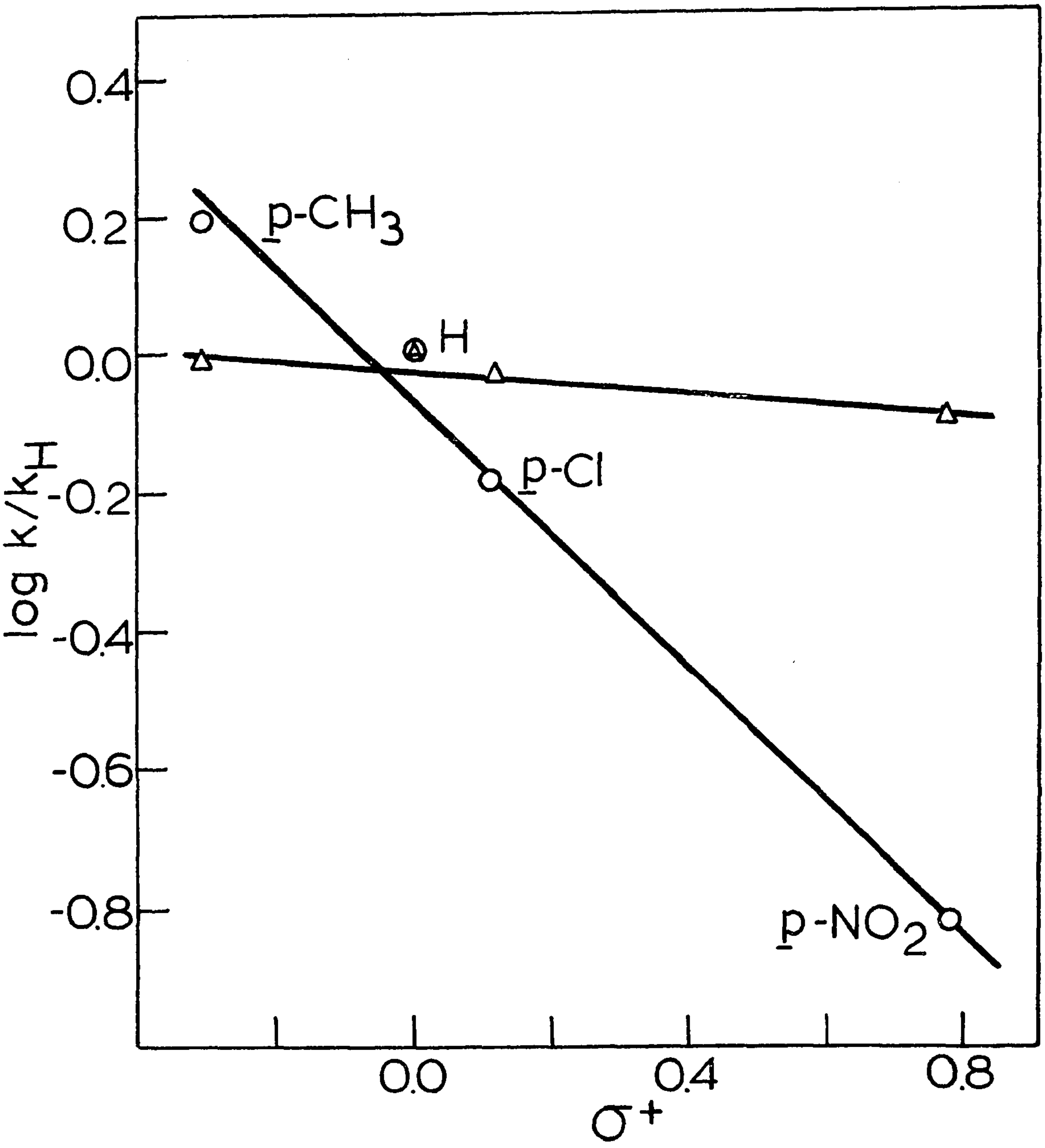

0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
log k/k$_H$
p-CH$_3$
H
p-Cl
p-NO$_2$
0.0
0.4
0.8
σ

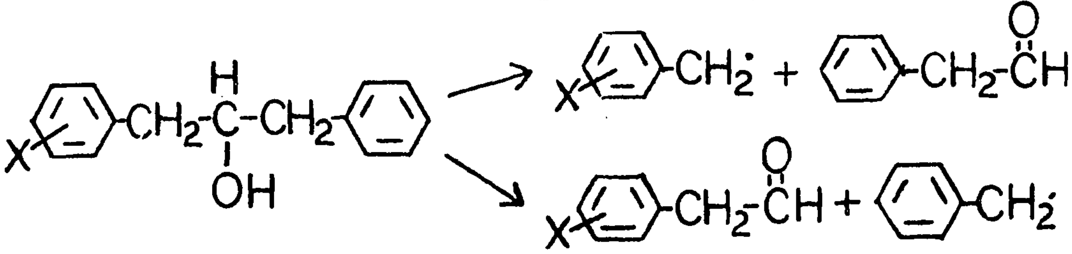
Figure 4. Hammett plots (σ^+) for cleavage (o) and ketone formation (Δ) in the chromic acid oxidation of 2-aryl-1-phenylethanols


0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
log k/k_H
p-CH3
H
p-Cl
p-NO2
0.0
0.4
0.8
σ+

constants and -0.09 ± 0.02 using σ^+. The ρ values for ketone formation are small, as expected, and in the direction expected. Primarily the ketone formation plots serve as a check for the methods of analysis since the expressions for both ketone formation and cleavage involve the same measurements. The correlation with σ constants are somewhat better than with σ^+; however, the difference is not great enough to make a distinction. In the case of cerium(IV) cleavage, the best correlation was obtained with σ^+ constants. As mentioned previously, some radical processes have been found to correlate best with σ constants and others with σ^+ constants. The value obtained for cleavage with either σ or σ^+ constants (ca. -1.0) is more in line with the other known radical processes than is the -2.0 obtained for cerium(IV) cleavage.

Oxidations of 1-aryl-2,3-diphenylpropan-2-ols

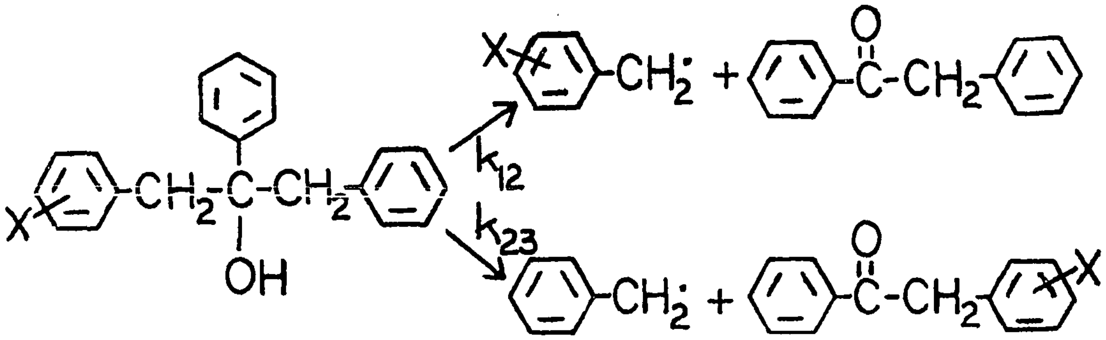
One possible explanation of the fact that a lower ρ value is obtained for cleavage with chromic acid than with cerium(IV) is that in the case of chromic acid, equilibrium is not obtained in complex formation. As mentioned in the section, General Considerations, this would lead to a smaller ρ value. Another possible explanation is that the expression for relative rates derived using the assumption that 1:1 complexes are formed may not be valid due to complications introduced by chromate diesters (13). In order to determine whether or not these complications were affecting the results, a system was chosen for oxidation in which the competition involved two modes of cleavage within the same molecule. The first system of this type studied was the 1-aryl-3-phenylpropan-2-ol system. Oxidation of one of these alcohols should lead to two different benzyl radicals and two different arylacetaldehydes.



The only products obtained in the chromic acid oxidation were the two benzaldehydes formed in approximately equal amounts. The benzaldehydes were expected as the final products of the benzyl radicals; however, the arylacetaldehydes should have also been formed. It was found that phenylacetaldehyde is rapidly oxidized under these conditions to give benzaldehyde as one of the products. The acid may have been formed also, but it would have been eliminated in the work-up procedure. Apparently phenylacetaldehyde is oxidized in the same manner as triphenylacetaldehyde (34). Since this system could not be used, the 1-aryl-2,3-diphenylethanol system was chosen to study the internal competition. This system was also studied using cerium(IV) as the oxidant to determine if the

ρ value obtained previously reflects the desired cleavage in this system as well.

Oxidations with both cerium(IV) and chromic acid were carried out in 85% acetic acid. Oxidation by cerium(IV) appeared to be slower than for the 2-aryl-1-phenylethanols. Oxidative cleavage of a tertiary alcohol by chromic acid requires the presence of a primary or secondary alcohol to produce the lower oxidation state of chromium which is responsible for cleavage. Secondary alcohols, however, were found to react so much more rapidly than the substrate, that they were completely oxidized without any cleavage having taken place in the substrate. This indicates that the oxidative cleavage of 1-aryl-2,3-diphenylpropan-2-ols by chromic acid is slower than that for 1,2-diarylethanols since ketone formation in the latter is analogous to the induced oxidation using a secondary alcohol. If cleavage were as slow for 1,2-diarylethanols, one would find only ketone and no cleavage products. Oxidation of 1-aryl-2,3-diphenylpropan-2-ols was finally achieved by inducing oxidation with an excess of 1-propanol along with a proportional amount of chromic acid. The slow rate for the reaction may be due to steric inhibition of complexation caused by a second benzyl group and a phenyl group. The oxidative cleavage of 1-aryl-2,3-diphenylpropan-2-ol is shown in Scheme 8.



Scheme 8. Oxidative cleavage of 1-aryl-2,3-diphenylpropan-2-ols

The relative rates of C_1-C_2 to C_2-C_3 cleavage were measured by the ratio of ketone produced.

$$\frac{d[Kt_{12}]}{d[Kt_{23}]} = \frac{k_{12}}{k_{23}}$$

$$\frac{k_{12}}{k_{23}} = \frac{[Kt_{12}]}{[Kt_{23}]}$$

Kt_{12} represents the ketone produced from C_1-C_2 cleavage and Kt_{23} represents that from C_2-C_3 cleavage. These are the same ketones which were produced in the oxidation of 2-aryl-1-phenylethanols by chromic acid. In this case, however, they are the products of the cleavage reaction rather than the products of normal oxidation.

The peak areas of each ketone in the CAN and chromic acid oxidations of 1-aryl-2,3-diphenylethanols along with the resulting values of k_{12}/k_{23} and log (k_{12}/k_{23}) are recorded in

Table 6b. The values obtained for log (k_{12}/k_{23}) are plotted against their σ^+ values. These plots appear in Figures 5 and 6.

The ρ values obtained were $-1.91 \pm .01$ for cerium(IV) oxidation and $-1.01 \pm .01$ for chromic acid oxidation. In the 2-aryl-1-phenylethanol system the values using σ^+ constants were -2.0 for cerium(IV) and -0.96 for chromic acid. The differences, then, are rather insignificant, and our original assumption for the 2-aryl-1-phenylethanol series that the substituent effect on the equilibrium of complex formation is very small, and that in both cases equilibrium complex formation is attained, must be valid. For the 1-aryl-2,3-diphenylpropan-2-ol system, although only three points were plotted, the correlation is much better with σ^+ constants than with σ constants. In the 1,2-diarylethanol system using chromic acid, the correlation was somewhat better with σ constants than with σ^+. It is felt that the data from the 1-aryl-2,3-diphenylpropan-2-ol system is probably better for the chromic acid oxidations since fewer measurements are involved. Only the ratio of the two ketone peaks is measured in this case; whereas, the 2-aryl-1-phenylethanol system requires the accurate measurement of the alcohol peaks, the ketone peaks, and the standard peak as well as an accurate weighing of each alcohol and the standard. If, indeed, correlation is better with σ^+ than with

Table 6b. Relative rates of C_1-C_2 and C_2-C_3 cleavage in the oxidation of 1-aryl-2,3-diphenylethanols by cerium(IV) and chromic acid

Alcohol	Oxidant	Peak Areas of Ketones		k/k_H [c]	$\log(k/k_H)$ [c]
		Kt_{12} [a]	Kt_{23} [b]		
p-CH_3	CAN	102	25	3.93	0.590±.004
		88	22	3.85	
p-Cl	CAN	30	49	0.614	-0.216±.003
		29	48	0.616	
p-CH_3	CrO_3	77	37	2.00	0.304±.003
		82	39	2.02	
p-Cl	CrO_3	50	65	0.769	-0.118±.004
		37	49	0.757	

[a] Ketone formed from C_1-C_2 cleavage.

[b] Ketone formed from C_2-C_3 cleavage.

[c] $k/k_H = k_{12}/k_{23}$.

Figure 5. Hammett plot (σ^+) for CAN oxidation of 1-aryl-2,3-diphenylpropan-2-ols

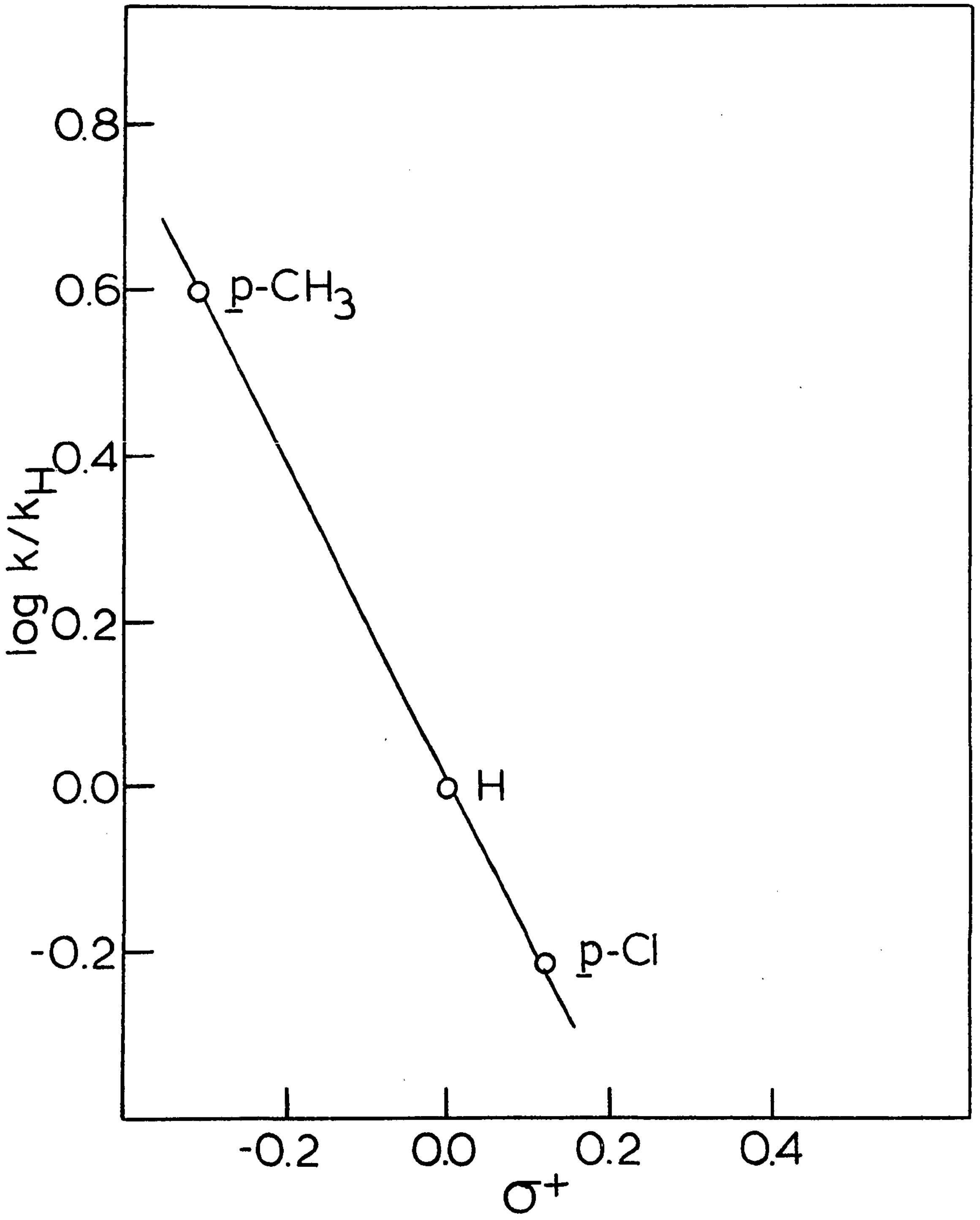
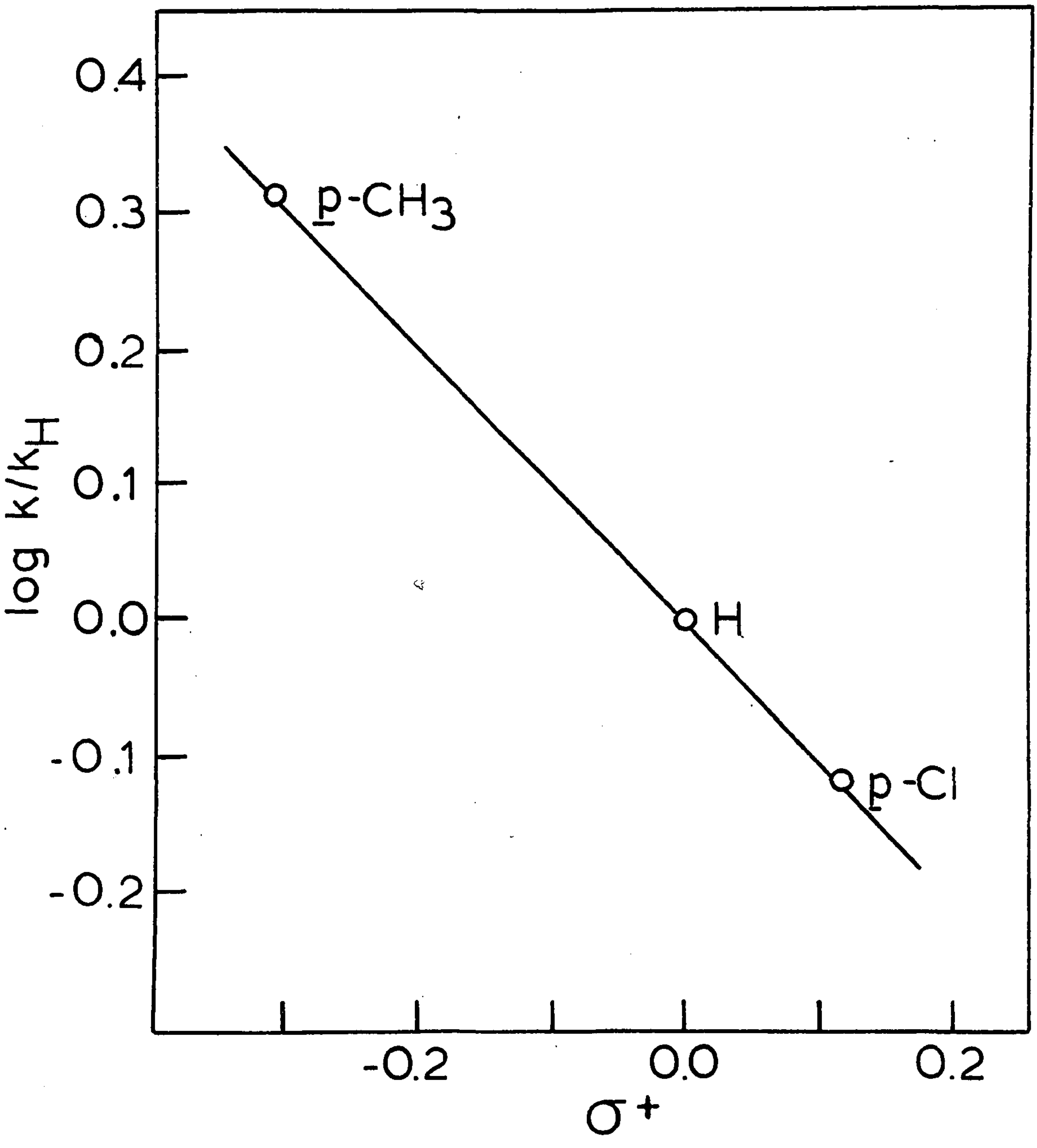

0.8
0.6
0.4
0.2
0.0
-0.2
log k/k_H
p-CH_3
H
p-Cl
-0.2
0.0
0.2
0.4
σ^+

Figure 6. Hammett plot (σ^+) for chromic acid oxidation of 1-aryl-2,3-diphenylpropan-2-ols

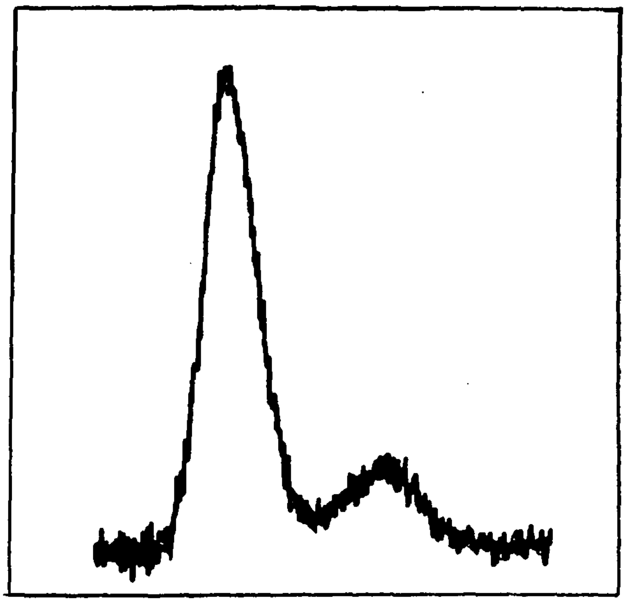

0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
log k/k$_H$
p-CH$_3$
H
p-Cl
-0.2
0.0
0.2
σ$^+$

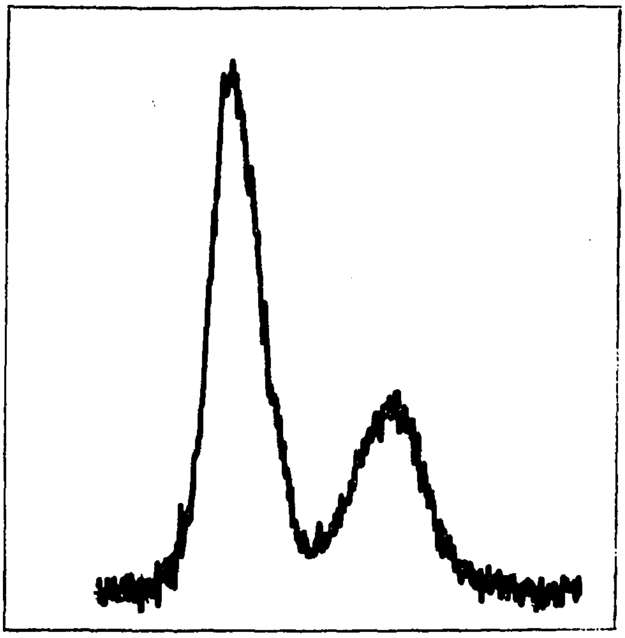
σ, a mechanism with a transition state analogous to that drawn for cerium(IV) cleavage, in which positive charge is developed on the benzylic carbon in the transition state (Scheme 7) due to some dispersal of the positive charge of the metal, can be drawn.

The difference between the chromic acid cleavage and cerium(IV) cleavage is vividly seen in the oxidation of 1-p-tolyl-2,3-diphenylpropan-2-ol. The expanded peaks for the two ketones are shown in Figures 7 and 8. The downfield peak is deoxybenzoin. Clearly there is a greater difference in the amount of each ketone produced in the cerium(IV) oxidation than in the chromic acid oxidation. This difference of $\rho= -2$ and $\rho= -1$ respectively cannot be due to differences involving the complexation step, since these results were obtained by internal competitions. Thus, the differences in cleavage by the two oxidants must lie in the transition state of complex decomposition. Several interrelated factors may be important here: the oxidation potentials of the two metals under these conditions, the effective charge on the metal ion, the stability of resonance forms such as resonance form B in Scheme 7, and the position of the transition state along the reaction coordinate. It would be difficult to determine what factors are responsible for the difference, especially since the intermediate chromium species which is responsible for cleavage is

Figure 7. Expansion of nmr signal of the methylene protons of the ketones produced from CAN oxidation of 1-*p*-tolyl-2,3-diphenylpropan-2-ol

Figure 8. Expansion of nmr signal of the methylene protons of the ketones produced from chromic acid oxidation of 1-*p*-tolyl-2,3-diphenylpropan-2-ol





short-lived.

Mechanism of Oxidative Cleavage

The overall mechanism for oxidative cleavage by these two oxidants involves equilibrium complex formation followed by complex decomposition in which the C-C bond is broken. That a free alkoxy radical is not formed is shown by the magnitude of the ρ values. All the data reported herein for both these oxidants supports a mechanism in which cleavage is a one-electron oxidation. In the case of chromic acid oxidations, these results are in opposition to the suggestion by Mosher and coworkers (6) that the first formed fragment is a cation. The findings of these workers that in the oxidation of substituted phenyl-*tert*-butylcarbinols, the ratio of cleavage products to ketone did not vary with the substituent, were interpreted as indication of a common alkoxonium ion for both processes. These results were not obtained by competition studies; furthermore, the substituent was on a 1-phenyl ring, which would measure aldehyde formation in the cleavage compared with ketone formation. The differences in these two processes might not be great enough to measure by this method. In the present work, there is clearly a change in the cleavage to ketone ratio thus ruling out any common intermediate. The results of Mosher and coworkers, as well as the present work, are best explained by the findings of Hampton, Leo, and Westheimer (11) that cleavage is brought about by a chromium species other than chromium(VI). If this species can only give rise to cleavage in aryl-*tert*-butylcarbinols and 2-aryl-1-phenylethanols, the amount of cleavage would be dependent upon the amount of the intermediate species formed and the rate of its reaction with the substrate compared with the rates of oxidation of those species which lead to ketone. As mentioned in the historical section, the recent findings by Roček and Radkowsky (7) and those by Wiberg and Schäfer (13) suggest that chromium(IV) is responsible for cleavage instead of chromium(V). If this is the case, one must offer a mechanism which would account for the yields of *ca*. 67% found by Hampton and coworkers (11). The experiment in which chromium(III) was added to the reaction mixture showed no change in the ratio of cleavage to ketone formation. Furthermore, it was found that the ratio of cleavage products to ketone does not vary significantly from 61% over the course of the reaction. These findings would rule out any interactions such as Cr(V) + Cr(III) → 2 Cr(IV). A mechanism which would account for up to 67% cleavage was suggested by Roček and Radkowsky (7). This mechanism, as adopted to the cleavage reaction, is shown in Scheme 9.

$$\mathrm{Cr(VI)} + \mathrm{RCHOHR'} \rightarrow \mathrm{Cr(IV)} + \text{ketone}$$

$$2\ \mathrm{Cr(IV)} + 2\ \mathrm{RCHOHR'} \rightarrow 2\ \mathrm{Cr(III)} + 2\ \mathrm{RCHO} + 2\ \mathrm{R}\cdot$$

$$2\ \mathrm{Cr(VI)} + 2\ \mathrm{R'}\cdot \rightarrow 2\ \mathrm{Cr(V)} + 2\ \mathrm{R'OH}$$

$$2\ \mathrm{Cr(V)} \rightarrow \mathrm{Cr(VI)} + \mathrm{Cr(IV)}$$

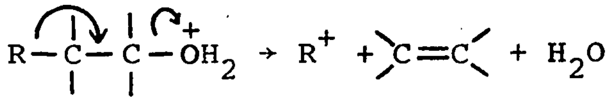
Scheme 9. Proposed mechanism showing chromium(IV) giving rise to 67% cleavage

This mechanism is dependent upon the disproportionation of chromium(V). The findings of Wiberg and Schäfer (13) that a measurable amount of chromium(V) builds up and then diminishes could be offered as weak support of this possibility. Certainly this mechanism could not be ruled out on the grounds that chromium(V) is not long-lived enough to disproportionate. Our findings that cleavage is by a one-electron mechanism and on the order of 60% would strongly support such a mechanism. In this scheme, chromium(V) is shown to be unreactive with the substrate compared with chromium(IV). If chromium(V) oxidation were competitive with chromium(IV) oxidation, a mechanism such as the one proposed by Westheimer and coworkers as their alternative mechanism (Scheme 2) would be operative. A consideration of both these mechanisms may offer an explanation for the increase in the ratio of cleavage to ketone formation upon the addition of sodium acetate (6, 11). Hampton and coworkers

(11) observed a sixteen-fold decrease in the overall rate of oxidation of phenyl-*tert*-butyl carbinol upon the addition of sodium acetate (0.05 *M*). This was shown to be due to the change in hydrogen ion concentration. This dependence of chromium(VI) oxidations upon hydrogen ion concentration was also observed by Wiberg and Schäfer (13). These workers also found that the effect of acid concentration on the oxidation by chromium(V) was of the same magnitude as that for chromium(VI) oxidation. Thus, sodium acetate should also retard the chromium(V) oxidation of the alcohol. If there is not a similar retardation in the oxidation by chromium(IV) or in the disproportionation step, the mechanism would be more like Scheme 9, and the cleavage to ketone formation ratio would be greater, with a maximum at 67%.

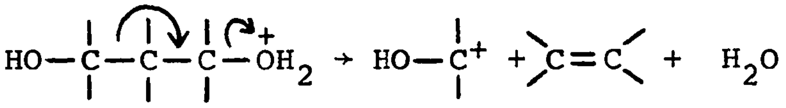
In chromic acid oxidations of alcohols of this type, both one-electron and two-electron oxidations occur simultaneously. The important point to note is that only the one-electron oxidation causes cleavage. Thus, in the two-electron oxidation, proton elimination is so favored over cation fragmentation that the latter does not occur. Even in the case of tertiary alcohols, where there can be no competition from an α-proton elimination, the reaction proceeds via elimination of the elements of water followed by oxidation of the olefin formed (14, 15). Thus, a two-electron fragmentation seems to be a rather poor process.

Fragmentations have been reported only for reactions which are thought to proceed through "hot" carbonium ions (53a) or which give extremely stable cations. For example, it has been found in the system,



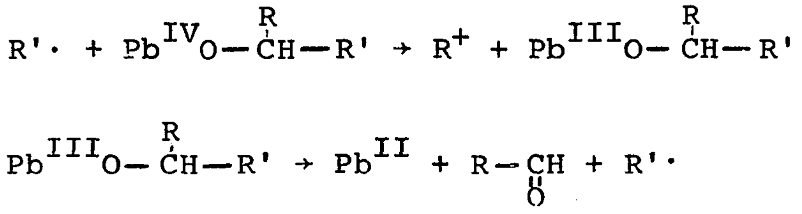
$$R-C-C-OH_2^+ \rightarrow R^+ + {>}C{=}C{<} + H_2O$$

that cleavage can occur when R = xanthyl but not when R = triphenylmethyl (53b). Whitmore has shown that such a process also occurs when a tertiary α-hydroxy cation is the fragment (54).



$$HO-C-C-C-OH_2^+ \rightarrow HO-C^+ + {>}C{=}C{<} + H_2O$$

The results discussed in the historical section, together with the results reported here, show that the cleavage reaction is the favored path for one-electron oxidations if a free radical of only modest stability can be formed. Thus, it seems probable that the metal ion oxidative cleavage for most monohydric alcohols is a one-electron process except in those cases which proceed via elimination of water followed by oxidation of the olefin. Thus, oxidative cleavage of phenyl-tert-butylcarbinol, which has been reported as one pathway for lead tetraacetate (19), chromic acid (10), and permanganate (20), and is the only pathway for the known one-electron oxidants (6, 8), is most likely in all cases a one-electron process leading to the tert-butyl radical and benzaldehyde. In the case of permanganate the lower intermediate manganese ions may be responsible for cleavage, as in the case of permanganate oxidations of α-hydroxy acids and the chromic acid oxidation of alcohols. The mechanism of Kochi and coworkers (33) for decarboxylation of acids by lead tetraacetate in which decarboxylation is brought about by lead(III) in a radical chain mechanism (Scheme 7) is worth considering for the fragmentation of alcohols. A mechanism analogous to the decarboxylation mechanism appears in Scheme 10.



$$R'\cdot + Pb^{IV}O-\overset{R}{C}H-R' \rightarrow R^{+} + Pb^{III}O-\overset{R}{C}H-R'$$

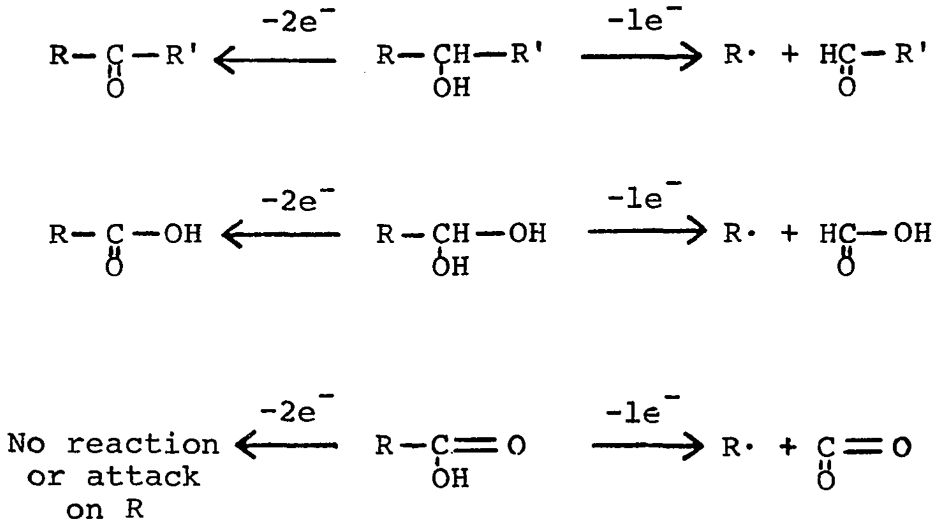
$$Pb^{III}O-\overset{R}{C}H-R' \rightarrow Pb^{II} + R-\underset{\overset{\|}{O}}{C}H + R'\cdot$$

Scheme 10. Suggested radical chain mechanism for fragmentation reactions of lead(IV) alkoxides

If the decarboxylation mechanism is correct, then this mechanism for lead alkoxide fragmentations seems like a good possibility.

The oxidative cleavage of diols is more complex (25). One-electron oxidative fragmentations of diols (12, 25) are known to take place, but the findings of Whitmore show that a tertiary α-hydroxy cation, which would be the fragment of a two-electron oxidation, can be ejected from carbonium ions (54). Also the situation is complicated by the possibility of chelation of the second hydroxy group.

It was shown in the historical section that the oxidative cleavage of aldehydes (hydrate form) and carboxylic acids in many cases bears a close resemblance to oxidative cleavage of alcohols. The oxidation of aldehyde hydrates and carboxylic acids might be considered as special cases of hydroxy compound oxidations as in Scheme 11.



$$R{-}\overset{}{\underset{\substack{\| \\ O}}{C}}{-}R' \xleftarrow{-2e^-} R{-}\underset{\substack{| \\ OH}}{CH}{-}R' \xrightarrow{-1e^-} R\cdot + H\underset{\substack{\| \\ O}}{C}{-}R'$$

$$R{-}\underset{\substack{\| \\ O}}{C}{-}OH \xleftarrow{-2e^-} R{-}\underset{\substack{| \\ OH}}{CH}{-}OH \xrightarrow{-1e^-} R\cdot + H\underset{\substack{\| \\ O}}{C}{-}OH$$

$$\begin{array}{c}\text{No reaction}\\ \text{or attack}\\ \text{on R}\end{array} \xleftarrow{-2e^-} R{-}\underset{\substack{| \\ OH}}{C}{=}O \xrightarrow{-1e^-} R\cdot + \underset{\substack{\| \\ O}}{C}{=}O$$

R = tert-butyl, benzyl, etc.

Scheme 11. Comparison of the oxidation of alcohols, aldehydes, and carboxylic acids

Such a consideration is in keeping with all the data on these reactions to date in light of the results obtained in the present work.

EXPERIMENTAL

Equipment

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

Gas liquid partition chromatography (glpc) analyses were performed on an Aerograph Model 200 instrument fitted with dual thermal conductivity detectors. Two columns were used. Column A was 5' by $\frac{1}{4}$" packed with 20% SE-30 on Chromosorb W. Column B was 5' by $\frac{1}{4}$" packed with 1,2,3-*tris*-(2-cyanoethoxy)propane on Chromosorb P.

Materials

1,2-Diphenylethanol

To a three-necked flask fitted with a reflux condenser, an addition funnel, and a magnetic stirrer were added 3.4 g (0.14 moles) of magnesium turnings and 300 ml of anhydrous ether. The mixture was stirred and 8.35 g (0.066 moles) of benzyl chloride (Matheson, Coleman, and Bell) was added slowly. To the sitrred Grignard reagent was added 7.0 g (0.066 moles) of benzaldehyde (Matheson, Coleman, and Bell). The reaction mixture was stirred an additional 45 min and hydrolyzed with 250 ml of a 20% ammonium chloride solution.

The ether layer was separated and the aqueous solution was extracted with three more 50-ml portions of ether. The combined ether extracts were dried ($MgSO_4$) and the ether was removed on a rotary evaporator. The crude product was recrystallized three times from hexane and methylene chloride to give 5.5 g (42%) of 1,2-diphenylethanol: mp 64-65°; lit (55) mp 66-67°; nmr ($CDCl_3$) δ 1.95 (s,1), 3.00 (d,2,*J*= 6.5 Hz), 4.86 (t,1,*J*= 6.5 Hz), and 7.3 (broad, 10).

For all experiments except the CAN oxidations in acetonitrile, the 1,2-diphenylethanol that was used was purchased from Eastman Organic Chemical Co. The purity was checked by glpc and nmr analysis.

1-*p*-Tolyl-2-phenylethanol

To 0.066 moles of the benzyl Grignard reagent was added 7.7 g (0.066 moles) of *p*-tolualdehyde (Aldrich) by the same procedure used for 1,2-diphenylethanol to yield 8.0 g (57.5%) of 1-*p*-tolyl-2-phenylethanol: mp 65-66°; lit (56) mp 68-69°; nmr ($CDCl_3$) δ 1.8 (broad s,1), 2.3 (s,3), 2.9 (d,2,*J*= 6.5 Hz), 4.7 (t,1,*J*= 6.5 Hz), and 7.1 (broad, 9).

1-Phenyl-2-*p*-tolylethanol

The same procedure was followed as for 1,2-diphenylethanol using 9.9 g (0.066 moles) of α-chloro-*p*-xylene (Aldrich) to make the Grignard reagent. The crude product was recrystallized from hexane to give 3.6 g (25.6% yield) of 1-phenyl-

2-p-tolylethanol: mp 43-45°; lit (57) mp 44.6-46.2°; nmr ($CDCl_3$) δ 2.07 (broad s,1), 2.29 (s,3), 2.90 (d,2, J= 6 Hz), 4.78 (t,1,J= 6 Hz), 7.02 (s,4), and 7.26 (s,5).

1-Phenyl-2-p-chloroethanol

The same procedure was followed as for 1,2-diphenylethanol using 10.6 g (0.066 moles) of α-p-dichlorotoluene to prepare the Grignard reagent. The crude product was recrystallized twice from hexane to give 3.5 g (23% yield) of 1-phenyl-2-p-chlorophenylethanol: mp 55-56°; lit (57) mp 55-56°; nmr ($CDCl_3$) δ 1.90 (broad s,1), 2.82 (d,2,J= 6.5 Hz), 4.75 (t,1,J= 6.5 Hz), and 7.2-7.7 (broad, 9).

p-Nitrobenzyl phenyl ketone

Following the method of Corey and Schaefer (58) with some modifications, 6 g (0.333 moles) of p-nitrophenylacetic acid (Aldrich) was treated with 50 g (0.364 moles) of phosphorus trichloride and the mixture was heated to reflux for 1 hr. To the cooled solution was added 400 ml of dry benzene, and the solution was decanted from the residue of phosphorous acid onto 55 g (0.467 moles) of anhydrous aluminum chloride (Baker). The mixture was refluxed and stirred one hour, cooled, and poured onto 500 g of crushed ice and 200 ml of concentrated hydrochloric acid. The precipitate was collected by filtration and dissolved in methylene chloride. The solution was dried ($MgSO_4$) and concentrated adding hexane occasionally. Upon standing, crystallization ensued. Recrystallization from methylene chloride and hexane gave 15 g (18.8% yield) of p-nitrobenzyl phenyl ketone: mp 143-144°; lit (58) mp 143-144°; nmr ($CDCl_3$) δ 4.4 (s,2), 7.2-7.7 (multiplet,5), and 7.9-8.3 (multiplet,4).

1-Phenyl-2-p-nitrophenylethanol

Using the method of Berti and Marsili (59) with some modifications, a solution of 0.5 g of sodium borohydride in 8 ml of 0.1 N sodium hydroxide was added to 6.5 g (0.027 moles) of p-nitrobenzyl phenyl ketone in 250 ml of methanol. The mixture was stirred overnight during which time the violet color disappeared. The solution was extracted with methylene chloride. Concentration of the methylene chloride solution followed by the addition of hexane gave precipitation of the product. The product was recrystallized twice from methylene chloride and hexane to give 5.0 g (76% yield) of 1-phenyl-2-p-nitropheylethanol as yellow needles: mp 90-91°; lit (59) mp 91-92°; nmr ($CDCl_3$) δ 2.13 (broad s,1), 3.12 (d,2,J= 6.5 Hz), 4.90 (t,1,J= 6.5 Hz), 7.30 (s and d,9,J= 9.0 Hz), and 8.10 (d,2,J= 9.0 Hz).

p-Methoxybenzyl phenyl ketone

Using the method of Jenkins (60), which involves the preparation of benzanisoin (by a benzoin condensation) followed by reduction with tin and hydrochloric acid, 25 g (29.4% yield) of p-methoxybenzyl phenyl ketone was obtained: mp 89-92°; lit (60) mp 89-92°; nmr (CCl_4) δ 2.4 (s,3), 4.25 (s,2), 7.3 (multiplet, 7), and 7.9 (d,2).

1-Phenyl-2-p-methoxyphenylethanol

To a 15% solution (0.5 g in 33 ml) of sodium borohydride in methanol was added 6 g (0.027 moles) of p-methoxybenzyl phenyl ketone dissolved in 50 ml of methanol, and the solution was stirred at room temperature overnight. Most of the methanol was removed on a rotary evaporator, and the residue was taken up in either (100 ml). The solution was washed twice with 20-ml portions of water and dried ($MgSO_4$). The ether was distilled, and the residue was recrystallized from hexane to give 5.4 g (90% yield) of white plates: mp 60-61°; lit (60) mp 61°; nmr ($CDCl_3$) δ 1.95 (broad s,1), 2.93 (d,2,J= 6.5 Hz), 3.75 (t,1,J= 6.5 Hz), 6.9 (multiplet, 4), and 7.3 (s,5).

1-Phenyl-2-m-methoxyphenylethanol

m-Methoxybenzaldehyde was converted to m-methoxybenzyl alcohol by reduction with lithium aluminum hydride. The alcohol was converted to m-methoxybenzyl chloride by treatment with thionyl chloride. The Grignard reagent was then prepared from the chloride and added to benzaldehyde.

m-Methoxybenzyl alcohol In a three-necked flask fitted with a condenser, an addition funnel and a mechanical stirrer were placed 5.5 g of lithium aluminum hydride and 250 ml of anhydrous ether. A solution of 20 g (0.15 moles) of m-methoxybenzaldehyde (Aldrich) in 50 ml of anhydrous ether was added dropwise. After the mixture stirred for two hours, water was added until bubbling ceased (about 20 ml). A 2% solution of hydrochloric acid was added until the white precipitate disappeared and only a milky white layer and a clear ether layer were present. The ether layer was separated, washed with saturated sodium bicarbonate, and dried ($MgSO_4$). Removal of the ether gave 18 g of crude product: nmr ($CDCl_3$) δ 3.65 (s,3), 3.70 (broad s,1), 4.48 (s,2), and 6.5-7.2 (multiplet,4).

m-Methoxybenzyl chloride Using the procedure of Cornforth and Robinson (61) with modifications, 16 g of thionyl chloride was added to a mixture of 18 g of crude m-methoxybenzyl alcohol in 10 g of pyridine. The mixture was stirred 3 hr below 30° after which 100 ml of ether and 50 ml of water were added. The ether layer was separated and washed three times with water and twice with an ammonium chloride solution. The solution was dried ($MgSO_4$) and the ether distilled leaving 15 g of the crude chloride: nmr ($CDCl_3$) δ 3.62 (s,3), 4.38 (s,2), 6.5-7.3 (multiplet,4).

1-Phenyl-2-m-methoxyphenylethanol Using the method of Alderová and Protiva (62) with a modified workup procedure, 15 g (0.096 moles) of the m-methoxybenzyl chloride was added to a stirred suspension of 5.5 g of magnesium turnings in 100 ml of ether. When the reaction had subsided, 9.0 g (0.085 moles) of benzaldehyde in 70 ml of ether was added slowly through the addition funnel. The mixture was hydrolyzed with 200 ml of 20% ammonium chloride solution. The layers were separated and the aqueous layer was extracted with three 50-ml portions of ether. The ether extracts were combined, washed with 50 ml of saturated sodium bicarbonate solution, and dried ($MgSO_4$). The ether was removed on a rotary evaporator leaving a yellow oil which was then distilled under vacuum. All of the fractions contained mixtures of products (by nmr). Those fractions which were thought to contain the desired product were chromatographed on a silica gel column $1\frac{1}{4} \times 12\frac{1}{2}$" eluting first with benzene then 10% ether in benzene. The fractions containing the alcohol were collected and the solvent was distilled leaving 0.7 g of 1-phenyl-2-m-methoxyphenylethanol: nmr (CCl_4) δ 2.15 (broad s,1), 2.83 (d,2,J= 6.0 Hz), 3.63 (s,3), 4.67 (t,1,*J*= 6.0), and 6.6-7.2 (multiplet,9).

1-Phenyl-2-*p*-acetylaminophenylethanol

p-Nitrobenzyl phenyl ketone was reduced by catalytic hydrogenation to give *p*-aminobenzyl phenyl ketone. Acetylation of the amino group with acetic anhydride produced *p*-acetylaminobenzyl phenyl ketone. Reduction with sodium borohydride gave 1-phenyl-2-*p*-acetylaminophenylethanol.

p-Aminobenzyl phenyl ketone   A 0.2 g sample of platinum oxide was suspended in 10 ml of 95% ethanol. The solution was flushed with hydrogen and then stirred vigorously under hydrogen at 1 atm pressure to reduce the catalyst. To the flask was added 4.5 g (0.019 moles) of *p*-nitrobenzyl phenyl ketone and stirring was continued until no more hydrogen was taken up. The solution was filtered and evaporated to 30 ml whereupon crystals began forming. The product was collected by filtration and recrystallized from methylene chloride and ether: mp 98-100°; nmr ($CDCl_3$)δ 3.50 (s,2), 4.12 (s,2), 6.8 (multiplet, 4), and 7.4-8.0 (broad,5).

p-Acetylaminobenzyl phenyl ketone   To 5 ml of acetic anhydride was added 3.0 g (0.014 moles) of *p*-aminobenzyl phenyl ketone. The solution was heated to reflux for two hours and poured into 50 ml of water. Upon cooling, a precipitate was formed which was collected by filtration. Recrystallization from ethanol yielded two crystalline products: Product 1, mp 158-160°; nmr ($CDCl_3$) δ 2.17 (s,3), 4.23 (s,2), and 7.1-8.1 (broad, 9); Product 2, mp 122°; nmr ($CDCl_3$) δ 2.3 (s,6), 4.3 (s,2), and 7.0-8.1 (broad, 9). The spectrum of Product 1 was consistent with that expected for the desired product. The spectrum of Product 2 was consistent with that expected for the diacetylated amide p-(N,N-diacetylaminobenzyl) phenyl ketone. Since Product 1 was contaminated with Product 2, both samples were suspended in 50 ml of water and heated for 1 hr. Upon cooling, filtering and drying, the desired product was obtained.

1-Phenyl-2-p-acetylaminophenylethanol To a suspension of 2 g of p-acetylaminobenzyl phenyl ketone in 50 ml of ethanol was added 10 ml of 10% sodium borohydride in ethanol. The solution was stirred for two hours in which time the color changed from violet to clear and the solution became homogeneous. The ethanol solution was concentrated, ether was added (100 ml), and the solution was washed twice with 20-ml portions of water. The ether was distilled and the residue was recrystallized from ether to give a 1.5 g of a white powdery precipitate; mp 134-136°; nmr ($CDCl_3$) δ 2.07 (s,1), 2.13 (s,3), 2.97 (d,2,J= 5.5 Hz), 4.82 (t,1,J= 5.5 Hz), and 7.00-7.35 (broad, 10).

Anal. Calculated for $C_{16}H_{17}NO_2$: C, 75.27; H, 6.71; N, 5.49. Found: C, 75.34; H, 6.74; N, 5.30.

α-p-Tolylacetophenone

In a procedure patterned after the method of Corey and Schaefer (58), 25 g of phosphorous trichloride was added to 25.0 g (0.147 moles) of p-tolylacetic acid (Aldrich). The mixture was refluxed 1 hr after which 200 ml of dry benzene was added and the solution was decanted from the residue of phosphorous acid onto 22.5 g of anhydrous aluminum chloride. The mixture was stirred 1 hr and poured onto 250 g of crushed ice and 100 ml of concentrated hydrochloric acid. The precipitate was removed by filtration and the two layers of the filtrate were separated. The benzene layer was dried ($MgSO_4$) and the solvent distilled. The precipitates were combined and recrystallized from methylene chloride and ether to give 7.3 g (23.5% yield) of α-p-tolylacetophenone: mp 95-96°; lit (63) mp 96.3-97.5°; nmr ($CDCl_3$) δ 2.1 (s,3), 4.1 (s,2), 7.1 (s,5), and 7.2-8.1 (multiplet, 4).

1-p-Chlorophenyl-3-phenylpropan-2-ol

In a three-necked flask fitted with a condenser, an addition funnel, and a mechanical stirrer were placed 3.4 g of magnesium turnings and 200 ml of anhydrous ether. The system was purged with nitrogen, and then a positive pressure of nitrogen was maintained above the condenser. A solution of 10.6 (0.066 moles) of α-p-dichlorotoluene (Aldrich) in 25 ml of anhydrous ether was added dropwise. To the Grignard reagent was added 7.7 g (0.065 moles) of phenylacetaldehyde (Aldrich) very slowly, and stirring was continued overnight. The reaction mixture was hydrolyzed with 250 ml of 20% aqueous ammonium chloride solution. The ether layer was separated, and the aqueous layer was extracted with two 50-ml portions of ether. The combined ether extracts were washed with 50 ml of 1 N sodium hydroxide, dried ($MgSO_4$), and concentrated on a rotary evaporator to give 10 g of an oil. Column chromatography was used to purify the product (7 x 40 cm column packed with silica gel). The column was eluted with pentane followed by benzene. The fractions which contained the product were combined and the solvent removed. After standing for some time, crystals began to form from the oily residue. Recrystallization from methylene chloride and hexane gave 3.0 g (18.8% yield) of the product: mp 40.5-41.5°; nmr ($CDCl_3$) δ 2.7 (multiplet, 4), 3.95 (multiplet, 1), and 7.1-7.4 (broad, 9).

Anal. Calculated for $C_{15}H_{15}OCl$: C, 73.02; H, 6.13; Cl, 14.37. Found: C, 72.75; H, 6.10; Cl, 14.42.

1-*p*-Chlorophenyl-2,3-diphenylpropan-2-ol

Deoxybenzoin was prepared by the reduction of benzoin with tin and hydrochloric acid. This ketone was added to the Grignard reagent prepared from benzyl chloride.

Deoxybenzoin After the manner of Jenkins (60), a mixture of 42 g (0.198 moles) of benzoin (Aldrich), 1.0 g of hydrated copper sulfate, 100 cc of ethanol and 70 cc of concentrated hydrochloric acid was refluxed 6 hr and filtered hot. Upon standing for some time in a cool place, a crystalline material formed which was filtered, washed with water and dried ($MgSO_4$) to give 35.5 g (91% yield) of the ketone: mp 56-58°; lit (64) mp 60°.

1-*p*-Chlorophenyl-2,3-diphenylpropan-2-ol In a three-necked flask fitted with a condenser, a mechanical stirrer, and an addition funnel were placed 3.4 g of magnesium turnings and 200 ml ether. To the stirred mixture was added 10.6 g (0.066 moles) of α-*p*-dichlorotoluene (Aldrich). Some heating was necessary to initiate the reaction. To the Grignard reagent a solution of 12.9 g (0.066 moles) of deoxybenzoin in 50 ml of ether was added very slowly giving a red coloration at the point of entry of the drop. When the red coloration no longer appeared, the addition of the ketone was ceased since it was found that further addition led to a large amount of unreacted ketone after hydrolysis. The reaction mixture was stirred an additional 45 min. and hydrolyzed with 250 ml of 20% aqueous ammonium chloride solution. The ether layer was separated and washed with 50 ml of saturated sodium chloride solution and dried ($MgSO_4$). The ether was removed on a rotary evaporator and the residue was recrystallized from methylene chloride and hexane to give 3.9 g (18.4% yield) of product: mp 76-77°; nmr ($CDCl_3$) δ 1.8 (broad s,1), 3.2 (multiplet, 4), and 6.8-7.3 (broad, 14).

Anal. Calculated for $C_{21}H_{19}ClO$: C, 78.10; H, 5.93; Cl, 14.37. Found: C, 78.28; H, 6.08; Cl, 14.42.

1-p-Tolyl-2,3-diphenylpropan-2-ol

The same procedure was used as for 1-p-chlorophenyl-2,3-diphenylpropan-2-ol, using 9.9 g (0.066 moles) of α-chloro-p-xylene to give 2.0 g (10% yield) of product: nmr ($CDCl_3$) δ 1.8 (broad s,1), 2.4 (s,2), 3.2 (multiplet, 4), 6.8-7.4 (broad, 14).

Anal. Calculated for $C_{22}H_{22}O$: C, 87.38; H, 7.33. Found: C, 87.05; H, 7.04.

Commercial chemicals

Table 7 lists the sources of chemicals obtained commercially.

Table 7. Commercial chemicals

Compound	Source
Ceric ammonium nitrate (CAN)	G. F. Smith
Chromium trioxide	Mallinckrodt
Acetonitrile	Mallinckrodt
Acetic acid	Baker
Sodium acetate (trihydrate)	Baker
Lithium aluminum hydride	Metal Hydrides
Sodium borohydride	Metal Hydrides
Benzyl alcohol	Baker
Acrylamide	Eastman
Acrylonitrile	Aldrich
Deoxybenzoin	Aldrich
Benzophenone	Aldrich
p-Methoxybenzophenone	Aldrich
p-Chlorobenzyl alcohol	Aldrich
Phenylacetaldehyde	Aldrich

Oxidations

Product study of the oxidation of 1-*p*-tolyl-2-phenylethanol by ceric ammonium nitrate

To 8 ml of a 0.25 *M* solution of ceric ammonium nitrate in 50% acetonitrite was added 1 mmole (0.212 g) of 1-*p*-tolyl-2-phenylethanol. A reflux condenser was attached, and the solution was heated on a steam bath until the red color disappeared and a light yellow color remained. To the cooled reaction mixture was added 8 ml of water, and the products were extracted with 10 ml of ether. The ether layer was dried ($MgSO_4$) and the products were analyzed by glpc on column A at a column temperature of 150°. The four product peaks obtained were enhanced by samples of benzaldehyde, benzyl alcohol, p-tolualdehyde, and benzyl nitrate in the approximate ratio of 1:2:4:1 respectively. The peak enhanced by benzyl nitrate was also enhanced by benzoic acid. The ether was evaporated from one of the samples, and the residue was taken up in deuterochloroform. A singlet appeared at 5.3 δ which was enhanced by benzyl nitrate. No acidic protons were observed. It should be noted that neither the glpc trace nor the nmr spectra showed a peak corresponding to benzyl-p-tolyl ketone. The one remaining peak of the glpc trace was enhanced by starting material, and, indeed, the nmr spectrum showed peaks corresponding to the alcohol.

Oxidation of deoxybenzoin by cerium(IV)

Deoxybenzoin was oxidized in the same manner as was 1-p-tolyl-2-phenylethanol. The reaction proceeded very slowly relative to the alcohol oxidations. Analysis by glpc gave peaks which were enhanced by starting material and benzil, and there were traces of cleavage products.

Competitive oxidations of 2-aryl-1-phenylethanols by cerium(IV) in aqueous acetonitrile

To 5 ml of 75% acetonitrile was added 0.40 mmoles of one of the 2-aryl-1-phenylethanols, 0.40 mmoles of 1,2-diphenylethanol, and 0.8 mmoles of ceric ammonium nitrate. A reflux condenser was attached and the mixture was heated over a steam bath 20 min. After cooling, 0.20 mmoles of the standard, benzophenone, was added. The solution was diluted with 10 ml of saturated sodium chloride solution, transferred to a separatory funnel and extracted with 10 ml of ether. The layers were separated and the ether layer was dried ($MgSO_4$).

Control solutions To 20 ml of 75% acetonitrile was added 0.40 mmoles of pinacol hydrate and 0.40 mmoles of ceric ammonium nitrate. After a few minutes at room temperature, the solution turned from deep red to clear. From this reduced cerium solution, three 5-ml aliquots were taken, and to each of these, 0.20 mmoles of each alcohol and 0.20 mmoles of benzophenone were added. These solutions were worked up in the same manner as the reaction mixtures.

Analysis by glpc The ether extracts of the competitive oxidations and the control mixtures were analyzed for unoxidized alcohol by glpc using column A. The temperature was programmed from 180° to 300° at 20°/min. Relative peak areas were determined by planimetry. The relationship between the relative peak areas and number of moles of alcohol present in the reaction mixture was determined for the control solutions. This relationship, which is dependent upon both the extraction ratio and the thermal conductivity ratio, is expressed by the factor X.

$$X = \frac{\text{mmoles standard}}{\text{mmoles compound}} \cdot \frac{A}{A'} \qquad (23)$$

A = area of compound peak

A'= area of standard peak

Since in this case mmoles of compound is equal to mmoles of standard, X is simply the ratio of peak areas. Values for the peak areas and the resultant values of X appear in Table 8.

The X values were used to determine the amount of each alcohol in the reaction mixtures by solving Equation 23 for mmoles compound. Values for the peak areas and the corresponding amount of unreacted alcohol appear in Table 9.

Radical trapping in CAN oxidations

Acrylamide In a three-necked flask fitted with an addition funnel, a stirrer, and a condenser were placed 40 ml of 75% acetonitrile, 0.212 g (1.0 mmole) of 1-*p*-tolyl-2-phenylethanol and 5 g of acrylamide. The system was purged with nitrogen, and then a positive pressure of nitrogen was maintained above the condenser. The mixture was heated over a steam bath and stirred as a solution of 0.8768 g (1.6 mmoles) of CAN in 10 ml of 75% acetonitrile was added slowly. A large amount of polymeric material was produced. Following the reaction, 150 ml of saturated

Table 8. Analysis of control solutions for competitive oxidations of 2-aryl-1-phenylethanols by CAN in 75% acetonitrile

Alcohol	Peak areas		X
	Alcohol	Standard	
p-H	154	162	0.96
	138	147	
	129	134	
	131	134	
p-CH_3	157	154	1.04
	143	135	
	130	124	
	119	113	
p-NO_2	142	154	0.94
	128	135	
	117	124	
	154	162	
	138	147	
	129	134	
	125	134	
m-CH_3O	84	94	0.90
p-AcNH	49	44	1.12
	60	55	
	83	72	
p-Cl	89	90	0.96
	99	101	
	83	87	
p-CH_3O	173	162	1.07
	160	145	
	142	134	
	141	134	

Table 9. Analysis for competitive oxidations of 2-aryl-1-phenylethanols by CAN in acetonitrile

Alcohols competing		Peak areas			mmoles	
A_1	A_2	A_1	A_2	Std	A_1	A_2
p-CH$_3$	*p*-H	52	135	95	0.106	0.297
		52	131	94	.107	.291
		56	135	97	.111	.291
p-Cl	*p*-H	146	113	116	.261	.203
		125	98	99	.261	.203
		137	104	108	.262	.201
p-NO$_2$	*p*-H	175	71	190	.196[a]	.077[a]
		131	56	144	.194[a]	.079[a]
p-CH$_3$O	*p*-H	19	201	200	.017[a]	.205[a]
		16	197	200	.016[a]	.200[a]
		20	200	200	.020[a]	.198[a]
m-CH$_3$O	*p*-H	-[b]	203	96	-[b]	.44
p-AcNH	*p*-H	-[b]	80	40	-[b]	.42
		-[b]	87	44	-[b]	.41

[a] Started with 0.2 mmoles of alcohol rather than 0.4 mmoles.

[b] Too small to measure.

sodium chloride solution and 50 ml of ether were added, and the products were extracted. The ether layer was separated and washed twice with 50-ml portions of 1 *N* sodium hydroxide, dried (MgSO$_4$), and concentrated. In a similar experiment, 25 g of acrylamide was used; however, the cerium solution was not added slowly. A control run was carried out in which conditions were identical except that no acrylamide was added.

Oxygen This experiment was carried out under the same conditions as the acrylamide trapping control experiment except that oxygen was allowed through the system as the reaction took place.

Product studies of chromic acid oxidations

To 10 ml of 85% acetic acid was added 0.16 g (1.6 mmoles) of chromium trioxide and 0.4752 g (2.4 mmoles) of 1,2-diphenylethanol. After four hours at room temperature the reaction mixture was transferred to a separatory funnel and 25 ml of saturated sodium chloride solution and 25 ml of ether were added. The products were extracted and the ether layer was washed twice with 10-ml portions of saturated sodium chloride and dried ($MgSO_4$). The ether was distilled and the residue taken up in deuterochloroform and analyzed by nmr. A similar oxidation was carried out with the reaction mixture 0.1 M in sodium acetate. Another experiment was carried out with the addition of 0.171 g (1.2 mmoles) of p-chlorobenzyl alcohol. The solution in this case was also 0.1 M in sodium acetate.

Competitive oxidations by chromic acid

To 7.5 ml of 0.16 M chromium trioxide in 85% acetic acid, which was 0.5 M in sodium acetate, was added 0.8 mmoles of the alcohols whose rates were to be compared. The solutions were heated on a steam bath 20 min. The reaction mixture was cooled and 0.565 g (0.2667 mmoles) of p-methoxybenzophenone was added. The solution was transferred to a separatory funnel and 15 ml of saturated sodium chloride solution and 15 ml of ether were added. After shaking two minutes, the aqueous layer was separated. The organic layer was washed twice with 15-ml portions of 1 N sodium hydroxide and dried over magnesium sulfate. The ether was distilled and the residue was taken up in deuterochloroform for analysis by nmr.

Control solutions A prereduced chromium solution was prepared by adding 1.6 g (16 mmoles) of chromium trioxide and 6.8 g of sodium acetate ($NaC_2H_3O_2 \cdot 3H_2O$) to 100 ml of 85% acetic acid. Pinacol (2.2 g) was added and the solution was heated on a steam bath until the green color of chromium(III) appeared. Control solutions were prepared by dissolving a known amount of an alcohol and its corresponding ketone, along with the internal standard (0.565 g, 0.2667 mmoles), in 7.5 ml of the prereduced chromium solution. These solutions were worked up in the same manner as the reaction mixtures.

Analysis by nmr Analysis for the alcohols, ketones, and standard for the control mixtures and the competitive oxidations was by the integration of the appropriate peaks of the nmr spectrum. In most cases the following conditions were used: filter bandwidth = 4.0 Hz, R. F. field = 0.08 mG, sweep width = 500 Hz, spectrum amplitude = 10, integral amplitude = 25, and integral sweep time = 100 sec. The peaks used were the methylene doublets of the alcohols (ca. 3.0 δ), the methylene singlets for the ketones (ca. 4.2 δ) and the methyl singlet for the standard p-methoxybenzophenone (3.8 δ). Three integral sweeps were made for each spectrum (controls and runs) and the average value was taken as the area. In the competition runs in which the p-nitro alcohol was one of substrates, there was enough separation in the alcohol doublets so that the downfield peak of the p-nitro alcohol and the upfield peak of the other alcohol could be measured. The other two peaks were superimposed. Because of this, a careful measurement was made in the control runs of the ratio of the upfield to the downfield peak of each alcohol measured in this manner. This ratio was found to be the same for all the alcohols as 45.0:55.0 (±0.01). Thus the amount of each alcohol was determined by measuring the one peak of the doublet that could be measured and multiplying by the appropriate factor to account for the other peak. In the cases of the p-methyl alcohol vs. the parent and for p-chloro vs. the parent, the separation was not so large for either the alcohols or the ketones. In these cases, expansions were made at 50 Hz with the R. F.

field lowered to a point below saturation (ca. 0.05). The area under each peak was measured by planimetry. The alcohol doublets in these runs overlapped such that one of the peaks of each doublet was between the two peaks of the other doublet. Thus, all four peaks could be measured.

The extraction ratios were determined for the control solutions in a manner analagous to the determination of thermal conductivity and extraction ratios for the glpc analysis. In this case the extraction ratio will be defined by Equation 24.

$$X = \frac{\text{mmoles standard}^{1}}{\text{mmoles compound}} \cdot \frac{A/H}{A'/H'} \qquad (24)$$

A/H = peak area per proton in compound

A'/H' = peak area per proton in standard

Values for the peak areas and the resulting X values appear in Table 10.

The X values were used to determine the amount of each alcohol and each ketone in the reaction mixtures by solving Equation 24 for mmoles compound. Values for the peak areas and the corresponding amounts of ketone and unreacted alcohol appear in Table 11.

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[1] In all cases mmoles standard = 0.2667 mmoles.

Table 10. Analysis of control solutions for competitive oxidations of 2-aryl-1-phenylethanols by chromic acid

Compound	mmoles compound	peak areas		X
		compound	standard	
p-H Alcohol	0.4	41.6	41.0	1.02
		31.0	30.0	
		42.0	40.8	
p-H Ketone	.4	43.0	41.0	1.06
		32.2	30.0	
		43.5	40.8	
p-NO_2 Alcohol	.4	47.5	50.0	0.956
		38.7	40.0	
		45.5	47.8	
p-NO_2 Ketone	.3	38.9	50.2	1.02
		40.2	52.0	
		37.0	48.8	
p-CH_3 Alcohol	.4	42.0	40.5	1.03
		51.4	49.2	
		45.2	45.2	
p-CH_3 Ketone	.4	43.0	40.5	1.06
		52.2	49.2	
		48.5	45.2	
p-Cl Alcohol	.4	50.9	50.2	1.02
		52.8	52.0	
		50.2	48.8	
p-Cl Ketone	.275	38.9	50.2	1.02
		40.2	52.0	
		37.0	48.8	

Table 11. Analysis for the competition oxidations of 2-aryl-1-phenylethanols by chromic acid

Alcohols competing		Peak areas					mmoles			
A_1	A_2	A_1	A_2	Kt_1^a	Kt_2^a	Std	A_1	A_2	Kt_1^a	Kt_2^a
p-CH$_3$	*p*-H	12.3	19.4	14.5	17.6	33.1	0.144	0.230	0.165	0.201
		22.5	30.4	19.5	23.5	39.5	.221	.301	.186	.224
		30.6	42.9	32.1	36.5	62.3	.193	.267	.194	.221
p-H	*p*-NO$_2$	12.2	40.0	23.2	31.1	42.5	.114	.396	.206	.287
		9.1	41.3	24.1	33.6	45.0	.079	.386	.204	.292
		11.6	40.8	24.8	30.8	44.2	.102	.388	.212	.273
p-Cl	*p*-NO$_2$	11.3	34.2	26.1	34.9	45.1	.098	.319	.226	.303
		13.8	45.0	34.4	45.6	59.0	.091	.321	.228	.303
		11.1	36.0	25.6	35.3	44.3	.095	.330	.218	.301
p-H	*p*-Cl	19.1	22.9	26.5	25.9	44.8	.150	.200	.223	.258

[a] Ketones derived from alcohols A_1 and A_2.

Attempted radical trapping in chromic acid oxidations by acrylamide and acrylonitrile

To 50 ml of an 85% acetic acid solution which was 0.1 M in sodium acetate was added 1.6 mmoles of chromic acid and 5 g of acrylamide or acrylonitrile. To this solution was added 1.2 mmoles of 1-*p*-tolyl-2-phenylethanol and the solution was heated over a steam bath until the color change occurred. To the reaction mixture was 150 ml of a saturated sodium chloride solution and 50 ml of ether. The ether layer was washed twice with 50-ml portions of 1 N sodium hydroxide and dried ($MgSO_4$). The ether was distilled, and the residue was taken up in deuterochloroform. Similar reactions using the same conditions but without the radical traps were also run. The products were analyzed by nmr.

Radical trapping in chromic acid oxidations by oxygen

To 5 ml of 85% acetic acid which was 0.5 M in sodium acetate was added 0.3168 g (1.6 mmoles) of 1,2-diphenylethanol and 0.08 g (0.8 mmoles) of chromic acid. The solution was heated on a steam bath under bubbling oxygen. The standard (0.565 g) was added and the solution was worked up in the same manner as the competition experiments. In a control experiment, nitrogen was bubbled through the solution instead of oxygen. In another control experiment, 0.0732 g (0.4 mmoles) of benzyl alcohol was added to 5 ml of the prereduced chromium solution which was used for the control solutions for the competitive oxidations. The workup and method of analysis for each of these control runs was the same as for the competition studies.

To 5 ml of 93% aqueous acetic acid which was 1 M in sodium acetate was added 0.212 g (1.0 mmole) of 1-p-tolyl-2-phenylethanol and 0.0533 g (0.533 mmoles) of chromic acid. The solution was heated under an oxygen atmosphere as above and worked up in the usual manner. Again, the control experiment was carried out under nitrogen.

Products as a function of time

To 12.5 ml of 85% acetic acid, which was 0.5 M in sodium acetate, was added 4 mmoles (0.7920 g) of 1,2-diphenylethanol. In another flask, 4 mmoles (0.4 g) of chromium trioxide was dissolved in 12.5 ml of the solvent. Both solutions were heated to 77° and flushed with nitrogen and then mixed and kept at 77° under nitrogen. Aliquots of 5 ml were taken after 1 minutes, 5 minutes, and 10 minutes and were added to 10 ml of a cooled, saturated sodium chloride solution. The standard, p-methoxybenzophenone (0.565 g) was then added along with 10 ml of ether and the workup was continued as for the competitive oxidations. The method of analysis was also the same as for the competition studies.

Effect of added chromium(III)

1,2-Diphenylethanol (1.6 mmoles) was dissolved in 7.5

ml of the pre-reduced chromium solution, and 1.2 mmoles of chromium trioxide was added. After heating on a steam bath 20 minutes, 7.5 ml of 85% acetic acid with 0.5 M sodium acetate was added along with 0.565 g of the standard. The workup was the same as for the competition studies. In the control experiment, the alcohol and chromium trioxide were dissolved in 7.5 ml of 85% acetic acid (0.5 M in sodium acetate). After heating as above, 7.5 ml of the prereduced chromium solution and 0.565 g of the standard were added and the mixture was worked up as before.

Competitive oxidations by CAN in acetic acid

The procedure for the CAN oxidation in 85% acetic acid was the same as for the oxidation in acetonitrile. The reaction mixture was heated just long enough for the color to change since prolonged heating produced the acetates of the starting materials. The workup was the same as that for chromic acid oxidations in acetic acid.

Control solutions The control solutions were prepared in an analogous manner to those for the acetonitrile runs. Workup was the same as for the competitive oxidations.

Analysis by glpc The same conditions were used as for the oxidations in acetonitrile. Values for the peak areas and the corresponding values of X appear in Table 12.

Table 12. Analysis of control solutions for competitive oxidations of 2-aryl-1-phenylethanols by CAN in 85% acetic acid

Alcohol	Peak areas		X
	Alcohol	Standard	
p-H	88	88	1.01
	95	94	
	89	87	
p-CH_3	92	88	1.06
	100	94	
	92	87	
p-Cl	86	92	0.94
	89	95	
	87	93	

Values for the peak areas and the corresponding amount of unreacted alcohol appear in Table 13.

Table 13. Analysis for competitive oxidations of 2-aryl-1-phenylethanols by CAN in 85% acetic acid

Alcohols competing		Peak areas			mmoles	
A_1	A_2	A_1	A_2	Std.	A_1	A_2
p-CH_3	p-H	74	199	136	0.102	0.290
		111	304	215	.097	.280
		65	173	122	.100	.281
		61	175	125	.092	.277
p-Cl	p-H	93	66	86	.230	.152
		97	65	94	.219	.137

Oxidation of 1-*p*-chlorophenyl-3-phenylpropan-2-ol

To a solution of 0.40 g (4.0 mmoles) chromic acid in 25 ml of 85% acetic acid at 70° was added 0.495 g (2.0 mmoles) of 1-*p*-chlorophenyl-3-phenylpropan-2-ol. Aliquots of 5 ml were taken after 2, 4, 8, 16, and 32 min and quenched in 10 ml of saturated sodium chloride solution. The workup was the same as all other oxidations in 85% acetic acid. The excess ether was distilled using a fractionating column. The samples were analyzed by glpc on column B with a column temperature of 120° and a flow rate of 60 ml/min.

Oxidation of phenylacetaldehyde

To 5 ml of 85% acetic acid was added 0.104 g (0.4 mmoles) of phenylacetaldehyde and 0.08 g (0.8 mmoles) of chromium trioxide. The solution was heated on a steam bath 10 min in which time the solution turned green. The workup was the usual for 85% acetic acid runs. Analysis by glpc was under the same conditions used for the analysis of the oxidation of 1-*p*-chlorophenyl-3-phenylpropan-2-ol.

Oxidation of 1-aryl-2,3-diphenylpropan-2-ols with CAN

To 7.5 ml of 85% acetic acid was added 0.8 mmoles of 1-*p*-chlorophenyl-2,3-diphenylpropan-2-ol or 1-*p*-tolyl-2,3-diphenylpropan-2-ol and 0.8768 g (1.6 mmoles) of CAN. The solution was heated over a steam bath 10 min. After cooling, the solution was made 0.5 M in sodium acetate in order to obtain a medium similar to that from which the extraction ratios for the α-arylacetophenones were determined. The workup was as usual for the 85% acetic acid experiments. The ratio of the two ketones produced was determined by the nmr expansion method used for chromic acid competitive oxidations.

Oxidation of 1-aryl-2,3-diphenylpropan-2-ols with chromic acid

To a solution of 0.60 g (6 mmoles) of chromic acid in 40 ml of 85% acetic acid was added 0.4 mmoles of one of the 1-aryl-2,3-diphenylpropan-2-ols. The mixture was heated over a steam bath and a solution of 0.24 g (4 mmoles) of 1-propanol in 10 ml of 85% acetic acid was added dropwise from an addition funnel. The reaction mixture was green when all the propanol had been added. The solution was made 0.5 M in sodium acetate and worked up as usual for 85% acetic acid runs, using proportional amounts of ether and the wash solutions in ratio to the amount of solvent. Analysis by nmr was the same as for the CAN oxidations.

SUMMARY

The cleavage reaction of alcohols by cerium(IV) and chromic acid was studied using the Hammett $\sigma\rho$ treatment on the relative rates of C-C cleavage of 2-aryl-1-phenylethanols. The ρ value for cleavage by cerium(IV), a known one-electron oxidant, was -2.0 using σ^+ constants. While this value is somewhat larger than ρ values obtained for other processes leading to benzyl radicals, it is closer to these values than to those for processes leading to benzyl cations. Trapping experiments with acrylamide and oxygen confirm the formation of benzyl radicals.

The oxidation of these alcohols in chromic acid leads to both ketone and cleavage products. The ρ value for cleavage was found to be _ca_. -1.0 using either σ or σ^+ values. Again there was evidence for radical trapping by oxygen although acrylamide was not an effective trap under these conditions. The ρ value for cleavage in this case lies in the normal range for processes leading to benzyl radicals; thus, it was concluded that the oxidative cleavage of alcohols by chromium acid is also a one-electron process.

For both oxidants, the same ρ values as the above were obtained from relative rates determined for the internal competitive cleavage in the system, 1-aryl-2,3-diphenylpropan-2-ol. These findings show that with both oxidants

cleavage proceeds via a rapid equilibrium complexation of the alcohol to the metal ion followed by a slow decomposition of the complex with homolytic C-C cleavage.

In general, the Hammett correlations for cleavage by both cerium(IV) and chromic acid were better for σ^+ constants than for σ constants. For other processes leading to benzyl radicals which show similar behavior, mechanisms are proposed in which there is some cationic character at the benzylic position in the transition state. Such a transition state would also be reasonable for the complex decomposition step of oxidative cleavage.

The finding that cleavage in chromic acid oxidations is a one-electron process coupled with some recent results of other workers suggests that the chromium species responsible for cleavage is chromium(IV) rather than chromium(V) as previously supposed. A mechanism suggested by Roček and Radkowsky (7) is consistent with these results and with the previous finding that maximum cleavage is 67%.

$$\mathrm{Cr(VI)} + \mathrm{RCHOHR'} \rightarrow \mathrm{Cr(IV)} + \text{ketone}$$

$$2\ \mathrm{Cr(IV)} + 2\ \mathrm{RCHOHR'} \rightarrow 2\ \mathrm{Cr(III)} + 2\ \mathrm{RCHO} + 2\mathrm{R'}\cdot$$

$$2\ \mathrm{Cr(VI)} + 2\ \mathrm{R'}\cdot \rightarrow 2\ \mathrm{Cr(V)} + 2\ \mathrm{R'OH}$$

$$2\ \mathrm{Cr(V)} \rightarrow \mathrm{Cr(VI)} + \mathrm{Cr(IV)}$$

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