Oxidation of Substituted Benzyl Alcohols with Ferrate(VI) Ion

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Summary A preliminary rate study of the reaction of potassium ferrate(VI) with several substituted benzyl alcohols has shown that electron-withdrawing substituents increase the rate of reaction and as well result in the largest intramolecular hydrogen–deuterium isotope effects; the results are discussed in terms of a suggested mechanism for the oxidation process.

THE ferrate(VI) ion in aqueous solution has been found to[1] specifically oxidize primary and secondary alcohols to aldehydes and ketones, respectively, in good yield under very mild conditions. Alkenyl compounds as well as tertiary alcohols were found to be unreactive under the experimental conditions employed.

To shed some light on the mechanism of ferrate(VI) oxidation of alcohols, we have determined the times for complete reaction, as well as the intramolecular hydrogen–deuterium isotope effects, for the reactions of three substituted benzyl alcohols (see Table). The reactions were carried out under the same conditions in all three cases. K_2FeO_4 (2·0 mmol) was added to an excess of substrate (3·0 mmol) in water. The time for the disappearance of the ferrate(VI) purple colour was taken as the time for the reaction.

TABLE

Rate and H/D *effects for ferrate*(VI) *oxidation of substituted benzyl alcohols at* 25°

Substituent	Time for complete reaction (min) Initial pH		k_H/k_D Initial pH	
	12·2	13·0	12·2	13·0
m-NO_2	1·6	0·8	7·9 ± 0·3	
H	3·3	1·3	6·1 ± 0·3	6·3 ± 0·3
p-OMe	5·3	3·0	5·3 ± 0·3	5·3 ± 0·3

A kinetic study of the ferrate(VI) oxidation of alcohols was unsuccessful because the stability of K_2FeO_4 depends on the pH and temperature of the solution.[2,3] Wagner[2] indicated that the rate of stirring of the K_2FeO_4 solution affects the reaction and Wrońska[3] established that the decomposition of K_2FeO_4 is catalysed by the ferric hydroxide precipitated during the reaction. Accordingly, we have determined the times for complete reaction when the substrate and ferrate(VI) concentrations were identical for the various compounds. The Table shows that the rate of reaction increases when the substituent is electron-withdrawing and decreases when the substituent is electron-donating. Also, an increase in the pH of the reaction medium leads to a shorter time for complete reaction for the three compounds studied.

Since we were unable to determine the rate constants for reaction of the substituted benzyl alcohols with ferrate(VI), we determined the intramolecular isotope effects to gain an insight into the mechanism of the oxidation reaction. α-d_1 Alcohols were oxidized according to reaction (1).

$$\mathrm{PhCHDOH} \xrightarrow{\mathrm{FeO_4^{2-}}} \mathrm{PhCHO} + \mathrm{PhCDO} \qquad (1)$$

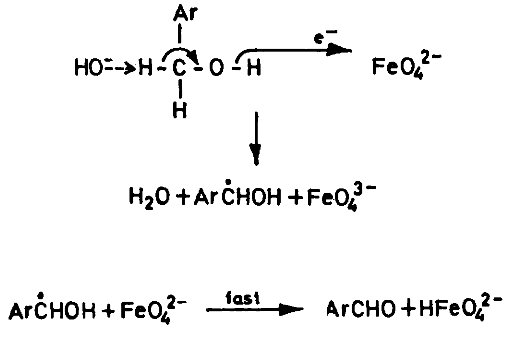
The α-d_1 alcohols were prepared by $LiAlD_4$ reduction of the purified benzaldehydes. The deuterium content of the m-NO_2, H, and p-OMe alcohols as determined by n.m.r. studies was 1·01, 0·99, and 0·99 atoms D per molecule, respectively. The mass spectrum of each of the three α-d_1 alcohols at low ionization voltage indicated the presence of less than one percent of both the non-deuteriated and dideuteriated species. The reaction products were analysed mass spectrometrically with the peak heights corresponding to the two aldehydes measured at 12 eV where subsequent fragmentation of the aldehydes and starting material was negligible.

The intramolecular hydrogen–deuterium isotope effects as determined for the three substituted benzyl alcohols (Table) represent a combination of both primary and secondary values. The secondary α-deuterium isotope effect is expected to be small,[4] less than 10 per cent, and consequently should not vary significantly with substituent on the benzene ring. The intramolecular isotope effects, therefore, should correspond very closely to normal primary effects[†] and indeed the value obtained for the m-NO_2 substrate is essentially at the theoretical maximum.[5]

[†] The primary kinetic isotope effect was determined by comparing the times for complete reaction of $PhCH_2OH$ and $PhCD_2OH$ with ferrate(VI) and was found to be 6·4 ± 0·4. This value, within experimental error, is the same as the intramolecular isotope effect.

Consequently, the rupture of the benzyl carbon–hydrogen bond must be involved in the slow rate-determining step for the oxidation process.

Consistent with the experimental results is a termolecular mechanism suggested by Stewart[6]‡ for the permanganate oxidation of alcohols. Hydroxide ion removes a proton (the rate effect is consistent with this process) while ferrate(VI) abstracts an electron (see Scheme). If this mechanism operates, ferrate(VI) cannot be abstracting a hydrogen atom or a hydride ion from the hydroxyl function since the time for complete reaction was essentially unchanged when the reaction was carried out in D_2O.



SCHEME

The increase in the magnitude of the hydrogen–deuterium effect when the substituent is made electron-withdrawing is also consistent with the termolecular mechanism. Such a mechanism requires that the proton be removed by base in the slow rate-determining step and this process, as observed, is facilitated by an electron-withdrawing substituent on the benzene ring. By making the removal of the benzylic hydrogen easier, it is predicted[7] that the transition state involving the rupture of the C–H bond should come earlier along the reaction co-ordinate resulting in less C–H bond weakening and a more reactant-like transition state.

The interpretation of the magnitude of a primary hydrogen–deuterium isotope effect in terms of the degree of carbon–hydrogen bond rupture at the transition state is difficult, however, since the hydrogen is involved in a three-centre displacement reaction. The generally accepted view is that the magnitude of this isotope effect is at a maximum when the transition state is symmetrical and that smaller values are a result of either reactant-like or product-like transition states.[5] Consequently, if one assumes that for the present reaction series the proton is more than one-half transferred to base at the transition state, then a decrease in C–H bond rupture when the benzylic hydrogen is made more acidic should lead to an increase in the magnitude of the primary hydrogen–deuterium isotope effect as observed.

It is concluded, therefore, that the transition state for the reaction of m-NO_2 benzyl alcohol is close to symmetrical since $k_H/k_D = 7{\cdot}9$ is near the theoretical maximum. Also, the transition states for the unsubstituted and p-OMe substrates are more product-like with increasing C–H bond weakening, since $k_H/k_D = 6{\cdot}1$ and $5{\cdot}3$ for the unsubstituted and p-OMe compounds, respectively.

It should be noted that the present mechanism involving the transfer of a proton to base is in accord with the predictions and observations of Swain *et al.*[8] These authors have presented theoretical reasons for expecting k_H/k_D isotope effects to vary considerably with substituents when a proton is transferred while hydride ion transfers are expected to be insensitive to substituents. These predictions were borne out by the experimental results obtained in a study of the oxidation of alcohols with bromine. Consequently, the large variation in k_H/k_D with substituent observed in the present study; *i.e.* 7·9, 6·1, and 5·3 for the m-NO_2, H, and p-OMe compounds, respectively, is in agreement with a proton transfer from carbon rather than a hydride ion.

The authors thank Miss Nona Pearson for assistance with the synthetic work and the National Research Council of Canada for financial support.

(*Received, August 9th*, 1971; *Com.* 1389.)

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‡ In ref. 1 we suggested a mechanism involving the transfer of a hydride ion from the benzylic carbon to the oxidizing agent. This proposed mechanism has now been shown to be inconsistent with our experimental results reported herein.

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