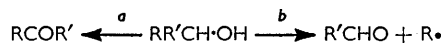**491.** *Oxidations of Organic Compounds by Cobaltic Salts. Part V.*[1]
*Kinetic and Product Studies, and Isotope Effects in the Oxidation of
Secondary Alcohols.**

By D. G. HOARE and W. A. WATERS.

Cobalt perchlorate concurrently oxidises secondary alcohols by two
routes,

$$RCOR' \xleftarrow{a} RR'CH{\cdot}OH \xrightarrow{b} R'CHO + R{\cdot}$$

the ease of elimination of an alkyl group other than methyl being comparable
or greater than the ease of oxidation by route (a). With alcohols RR′CD·OH
both product studies and rate measurements reveal that these oxidations
exhibit kinetic isotope effects, but concordance between the two sets of
measurements is not clearly apparent. Suggestions are advanced concerning
the reaction mechanism.

EXTENSION of Part IV [1] to product and kinetic studies of the oxidations of a number of
primary and secondary alcohols, including three α-deuterated alcohols, by cobaltic
perchlorate is reported below. The product studies are consistent with the simple reaction
mechanisms of Parts I [2] and IV,[1] but the kinetic studies show some rather unexpected
features concerning which tentative suggestions only can be made.

Product Studies.—Table 1 shows that aldehydes are major products when secondary
alcohols are oxidised by a small proportion of cobaltic perchlorate. From these results
it is possible to calculate the relative rates of oxidation by the two competitive routes,
to yield aldehydes or ketones.

---

[1] Preceding Paper.
[2] Hoare and Waters, *J.*, 1962, 965.

Taking, from Part IV, the relative elimination rates $Et : Pr^n : Pr^i = 100 : 34 : 2300$, the oxidation of the n-propylcarbinol ($CHMePr^n\cdot OH$) gives $H = 36 \pm 3$, that of the isopropyl-carbinol ($CHMePr^i\cdot OH$) gives $H = 39 \pm 16$ and that for diethylcarbinol ($CHEt_2\cdot OH$), again in 1·57M-perchloric acid, gives $H = 41 \pm 8$, note being taken that in

TABLE 1.

Product yields from oxidations of alcohols.

(a) $[HClO_4] = 1\cdot57M$; initial $[Co^{III}]$ *ca.* 0·03M; temp. 15°.

Alcohol	[Alcohol], M	Product ratios	Notes
RCHMe·OH		MeCHO : RCOMe	
Pr^{n}CHMe·OH	0·54	49 : 51 $\pm$ 5	in 50% MeCN
Pr^{i}CHMe·OH	0·28	98·3 : 1·7 $\pm$ 1·2	in 25 and in 50% MeCN

(b) Oxidations of $Et_2CH\cdot OH$ and $Et_2CD\cdot OH$ in 50% MeCN; initial [alcohol] = 0·28M; initial $[Co^{III}]$ *ca* 0·03M; temp. 15°.

Acidity [HClO$_4$], M	Product ratios EtCHO : Et$_2$CO	Overall yield %	Notes
2·98	98·9 : 1·1	52	
1·57	82·9 : 17·1 $\pm$ 4	81	3 experiments
1·57	93·6 : 6·4 $\pm$ 0·4	—	Et$_2$CD·OH used
1·05	71·9 : 28·1	75	
1·05	90·8 : 9·2	61	1·2M-acrylamide added

Products were identified by their R_F values on chromatography; EtCHO was isolated as its dinitrophenylhydrazone. Yields are calculated for the initial reaction, Alcohol + 2Co^{III} ⟶ carbonyl compounds, and would only be 100% if secondary oxidation did not occur.

this oxidation the elimination of either ethyl group would leave EtCHO. For the deuterated alcohol, the same statistical correction being used, one gets $D = 13\cdot7$ and therefrom a product kinetic isotope effect $k_H/k_D = 3 \pm 0\cdot5$.

However, with diethylcarbinol the product ratio EtCHO : Et$_2$CO is acid-dependent. The addition of acrylamide reduces the yield of diethyl ketone without affecting the yield of acetaldehyde, as would be expected if there was a carbon radical as a precursor of diethyl ketone [*i.e.*, path (i) and not path (ii)], but not of acetaldehyde (compare Part I).

$$(1) \quad Et_2CH\cdot OH + Co^{III} \longrightarrow Et_2\dot{C}\cdot OH + Co^{II} + H^+$$

$$(2) \quad Et_2CH\cdot OH + Co^{III} \longrightarrow Et_2CHO\bullet + Co^{II} + H^+ \xrightarrow[\text{fast}]{Co^{III}} Et_2CO + Co^{II} + H^+$$
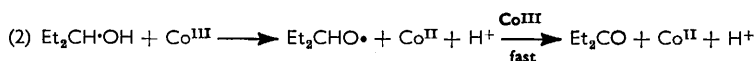
Again, our data on cyclohexanol oxidation (Table 2) suggest that there may be more C–C cleavage with the α-deuterated alcohol (k_H/k_D about 1·3), that this is not noticeably changed when the solvent is 50% aqueous methyl cyanide, but that formation of cyclohexanone is almost eliminated when acrylamide has been added to trap the intermediate carbon radical from a reaction (1).

The inferences from these product studies are (a) that the elimination of an alkyl radical and the elimination of hydrogen are different, though concurrent reaction processes, and (b) that the rate of oxidation of a secondary alcohol to a ketone,

$$R_2CH\cdot OH + 2Co^{III} \longrightarrow R_2CO + 2Co^{II} + 2H^+$$

is comparable to the rate of oxidation of a tertiary alcohol containing alkyl group other than methyl.

Kinetic Studies.—Table 3 gives our measurements of the rate constants for $-d[Co^{III}]/dt$ for a number of primary and secondary alcohols in various methyl cyanide–water mixtures at 15° and Table 4 gives data from which activation energies and entropies

have been calculated. Table 5 gives comparative rates extrapolated to aqueous solution by means of the empirical equation $k_{solv.} = k_{water} \exp(Mx)$ of Part IV together with values of the constant M.

For diethylcarbinol, the isopropyl-carbinol, cyclohexanol, and their α-deuterated analogues values of the kinetic isotope effects are set out in Table 6.

<div align="center">

TABLE 2.

Oxidations of cyclohexanol.

$[HClO_4] = 1.57M$; initial $[Co^{III}]$ *ca.* 0.03M; temp. 15°.

</div>

Conditions	Alcohol (M)	$10^6 \times [Co^{III}]$ consumed	$10^6 \times$ [ketone] formed	Yield of ketone (averages) (%)	
a	0.10	23.4	8.9	76	
a	0.11	23.4	7.3	63	
a	0.15	24.3	8.2	68	
a	0.17	21.3	8.0	75	
a	0.20	24.3	7.9	65	
a	0.24	15.7	6.0	77	
a	0.26	23.4	9.4	80	72 ± 8
a, b	0.17	19.2	1.3	*14*	
c	0.17	23.4	9.7	82	
c	0.24	15.7	6.0	77	79 ± 3
Deuteroalcohol					
a	0.17	15.7	4.0	51	
a	0.19	23.4	7.2	62	57 ± 6
c	0.19	23.4	7.0	60	
c	0.27	15.7	4.4	56	58 ± 3

a, Aqueous solution; *b*, 1.0M-acrylamide added; *c*, 50% aqueous methyl cyanide.

Table 6 shows that, for cobaltic perchlorate solutions of constant acidity the kinetic isotope effects, which in water differ for each alcohol, diminish on the addition of methyl cyanide as the co-solvent and vanish in about 60% methyl cyanide. However, for cyclohexanol k_H/k_D is not noticeably temperature-dependent.

To reconcile these values with the product data of Table 1 is a theoretical problem. Firstly, $-d[Co^{III}]/dt$ for diethyl ketone has scarecely any kinetic isotope effect, but the product ratio shows that elimination of hydrogen from $Et_2CH\cdot OH$ is 3 times as easy as that of deuterium from $Et_2CD\cdot OH$. Even granted that only 17% of the measured oxidation involves the breaking of an α-C–H or C–D bond then, assuming $k_H/k_D = 1$ for alkyl-radical elimination, the kinetic isotope effect, measured from $-d[Co^{III}]/dt$ should be 1.13 ± 0.01, which is above our limits of experimental error. Secondly the isopropyl-carbinol shows, for $-d[Co^{III}]/dt$, a kinetic isotope effect of quite 1.3 in water and yet 98% of its oxidation is to acetaldehyde in which the α-C–H is not broken. Admittedly our product studies have been conducted at higher [Alcohol] : [Co^{III}] ratios than our kinetic measurements, but even with the latter the ratios have been far too high for our rate data to be influenced significantly by secondary reactions.

It is therefore necessary to consider closely the mechanistic implications of measurements of $-d[Co^{III}]/dt$ for oxidations of alcohols. In Parts I [2] and IV [1] we postulated the reaction scheme $ROH + Co^{III} \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} (ROH, Co^{III}) \xrightarrow{k_2}$ Products, suggesting that the pre-equilibrium constant $K(= k_1/k_{-1})$ was small and $k_1 \gg k_2$ since the reactions had simple second-order and not Michaelis–Menten kinetics. However, second-order kinetics would also be found if $k_1 < k_2$ but in this case only a trivial kinetic isotope effect would be observed with secondary alcohols and the M values for the solvent effect should be almost identical for $R_2CH\cdot OH$ and $R_2CD\cdot OH$.

TABLE 3.

Rate constants for oxidations of primary and secondary alcohols.

$\{-d[\mathrm{Co^{III}}]/dt = k[\mathrm{Co^{III}}][\mathrm{ROH}]; \ k$ in l. mole^{-1} sec.$^{-1}\}$. $[\mathrm{HClO_4}] = 1\cdot57\mathrm{M}$; initial $[\mathrm{Co^{III}}]$ *ca.* $0\cdot002\mathrm{M}$; temp. 15°. The percentage of methyl cyanide in the solvent is given in brackets after the rate constant.

Section (a)

Alcohol	$10^2 \times$ Molarity	Rate constants, k				
MeOH	0·78	118	(0·0)			found
	1·94	114	(0·0)			,,
	10·6	123	(0·0)			,,
Me$_2$CH·OH	0·73	37·0	(0·0)			,,
	2·93	38·5	(0·0)			,,
	5·65	35·4	(0·0)			,,
EtOH	0·50	297(1·6)	451(11·6)	860(31·6)		found
		304	437	907		calc.
Pr^{n}OH	0·99	304(1·6)	423(10)	755(30)		found
		304				calc.
CHMeEt·OH	3·33	74·0(4)	154(20)	214(30)		found
		75	147	224		calc.
CHMePr^{n}·OH	2·55	73·0(4)	153(20)	228(30)	439(50)	found
		75	148	228	536	calc.
CHEt$_2$·OH	2·82	113(1·6)	206(20)	301(30)	570(50)	found
		112	209	293	576	calc.
CDEt$_2$·OH	1·85	111(1·6)	257(25)		508(50)	found
		111	257		635	calc.

Section (b)

% of methyl cyanide...	0	10	20	30	40	50	60
Cyclohexanol							
$10^3 \times$ molarity	62·6	—	62·6	6·26	6·26	6·26	6·26
10^3k (found)	49·7	—	138	216	399	648	1080
10^3k (calc.)	49·7	—	133	218	—	—	—
1-*Deuterocyclohexanol*							
$10^3 \times$ molarity	48·5	—	48·5	48·5	4·85	4·85	4·85
10^3k (found)	26·8	—	83·0	139	342	570	1030
10^3k (calc.)	28·8	—	83·1	145	—	—	—
CHMePr^{i}·OH							
$10^3 \times$ molarity	55·8	57·0	55·8	55·8	—	57·0	—
10^3k (found)	344	397	439	551	—	623	
10^3k (calc.)	345	392	458	531	—		
CDMePr^{i}·OH							
$10^3 \times$ molarity	57·4	9·20	57·4	9·20	—	9·20	—
10^3k (found)	249	322	382	478	—	655	
10^3k (calc.)	255	310	382	471	—		

The calculated rates for mixed solvents correspond to the equation

$$k_{\mathrm{solv.}} = k_{\mathrm{water}} \exp (Mx) \text{ of Part IV.}$$

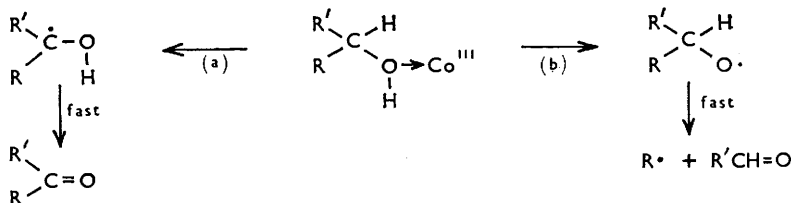Our product studies indicated that the reaction complex can break down by concurrent routes (a) and (b)

TABLE 4.

Temperature-dependence of oxidation rates.

$[HClO_4] = 1.57M$; initial $[Co^{III}]$ *ca.* 0.002M.

Cyclohexanol (in water)	5°	10°	15°	20°	25°
$10^2 \times$ molarity	9.4	—	6.26	6.26	6.26
10^3k (l. mole^{-1} sec.$^{-1}$)	6.83	19.4 [a]	49.7	130	311
1-Deuterocyclohexanol (in water)		10°	15°	20°	25°
$10^2 \times$ molarity		—	4.85	—	7.28
10^3k (l. mole^{-1} sec.$^{-1}$)		11.0 [a]	26.8	—	173
k_H/k_D		1.76	1.85	—	1.80
Diethylcarbinol (1.6% of MeCN)	5°	10°	15°	20°	25°
$10^2 \times$ molarity	2.7	2.7	2.82	2.7	2.7
10^3k (l. mole^{-1} sec.$^{-1}$)	16.0	43.8	113	280	634
Isopropyl alcohol (in water)	5°	10°	15°	20°	25°
$10^2 \times$ molarity	4.92	—	—	4.92	4.92
10^3k (l. mole^{-1} sec.$^{-1}$)	5.1	11.8	37	81	181
t-Butyl alcohol (in water)		10°	15°	20°	25°
$10^2 \times$ molarity			64.8	48.3	48.3
10^3k (l. mole^{-1} sec.$^{-1}$)		0.681 [b]	2.16	5.27	13.2

Hence:

Cyclohexanol	Diethylcarbinol	Isopropyl alcohol	t-Butyl alcohol
E, 31.5 kcal./mole	E, 29.8 kcal./mole	E, 29.6 kcal./mole	E, 32.1 kcal./mole
$\Delta S^{\ddagger}$, +43.0 e.u.	$\Delta S^{\ddagger}$, +38.5 e.u.	$\Delta S^{\ddagger}$, +35.5 e.u.	$\Delta S^{\ddagger}$, +38.7 e.u.

a, Data from Part I. *b,* Interpolated from data in Part I.

TABLE 5.

Rate constants for oxidations of primary and secondary alcohols.

$\{-d[Co^{III}]/dt = k[Co^{III}][Alcohol]\}$. $[HClO_4] = 1.57M$; initial $[Co^{III}]$ *ca.* 0.002M; temp. 15°. k_0 values for water are calculated from $k_{soln.} = k_{water} \exp (Mx)$.

Alcohol	$10k_0$ (l. mole^{-1} sec.$^{-1}$)	M	Alcohol	$10k_0$ (l. mole^{-1} sec.$^{-1}$)	M
MeOH	1.18	—	CHMe$_2$·OH	0.37	—
EtOH	2.86	3.7	CHMeEt·OH	0.635	4.2
Pr^{n}OH	2.89	3.2	CHMePr^n·OH	0.631	4.3
Pr^{i}OH	0.37	—			
CH$_2$Pr^i·OH	3.37	1.54	CDMePr^i·OH	2.51	2.10
CHEt$_2$·OH	1.06	3.7	CDEt$_2$·OH	1.05	3.6
Cyclohexanol	0.497	4.9	[1-D]cyclohexanol	0.268	5.6
Me$_3$C·OH *	0.0216	6	CMe$_2$Et·OH	0.50	3.8

* From Part IV.

TABLE 6.

Kinetic isotope effects (k_H/k_D) in methyl cyanide–water mixtures (at 15°).

| MeCN % (v/v)	0	10	20	30	40	50	60
Cyclohexanol	1.85	—	1.66 (25%)	1.55	1.17	1.12	1.05
CHEt$_2$·OH.......................	1.02	—	90.6		—	1.00	—
CHMePr^i·OH	1.38	1.23	1.15	1.15	—	0.95	—

and evidently the ratio $k_a : k_b$ is affected by (i) the acidity and (ii) the solvent environment. This is rational since both these factors can influence the reaction complex, which has 5 other ligand groups attached to the cobalt. According to this concurrent reaction theory the overall kinetic isotope effect, measured by $-d[Co^{III}]/dt$ should be much less than that for the route (*a*) alone, since it is assumed to be unity for the Co–O bond fission (*b*). Another possibility (suggested to us by Dr. J. S. Littler) is that the known fast reaction

(3) $R_2CHO\bullet + HCR_2\bullet OH \longrightarrow R_2CH\bullet OH + \bullet CR_2\bullet OH$

competes, in reaction (*b*) above, with the elimination of an alkyl group

(4) $R_2CH\bullet O\bullet \longrightarrow R\bullet + RCH=O$

View Online

[1964] *Organic Compounds by Cobaltic Salts. Part V.* 2565

In this case the production of ketone could involve both product and kinetic isotope effects (route *a*), or a product isotope effect without a kinetic isotope effect (route *b*, reaction 3). This scheme affords the simplest explanation of our findings concerning the oxidation of diethylcarbinol and cyclohexanol. However, our findings concerning the isopropyl-carbinol (CHMePr^i·OH) cannot be explained unless we deduce that Co–O fission (*b*), followed by reaction 4, is the predominent reaction path in this case, and that the Co–O fission (*b*) has a kinetic isotope effect k_H/k_D 1·3; however, the latter deduction is inconsistent with the data for diethylcarbinol. Thus it appears that we must seek for explanations in differences in energy levels of the complexes (I) and (II).
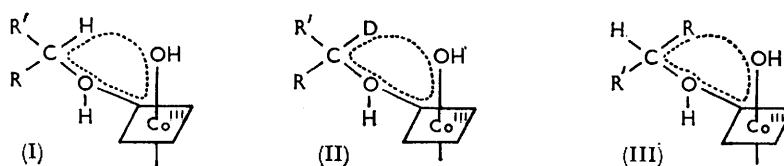
Now, the reaction process involves the abstraction of one electron from the alcohol ligand by pairing with a *d* electron of the Co^{III} ion, which must be in the high-spin form so that a vacant *d* orbital is available (see Part I). As our diagrams indicate the spatial distribution of this *d* orbital overlaps the whole of the CH(OH) or CD(OH) groups of the alcohols so that there is resonance interaction with the electrons of the C–H and C–O bonds, both of which must therefore be involved when the complexes decompose. Thus even for eventual fission to a radical, RR′CH·O·, there may be a kinetic isotope effect similar to secondary isotope effects found for disruption of X–Y in compounds H–C–X–Y and D–C–X–Y. In this way one could account for the kinetic isotope effect with the isopropyl-carbinol (CHMePr^i·OH) but not for the absence of a kinetic isotope effect with diethylcarbinol. These are however conformations, *e.g.*, (III), in which participation of C–H is negligible and with which kinetic isotope effects k_H/k_D should be practically unity.

Conformation (III) indicates that the ease of oxidation of secondary and tertiary alcohols may also be related to the ease of fission of C–alkyl bonds, and in this way one would correlate the product and kinetic studies of Part IV. This approach, however, does not account for certain mechanistic distinctions between aldehyde and ketone formation upon which we have already commented.

EXPERIMENTAL

Materials.—3-*Deutero*-3-*pentanol* was prepared by reducing diethyl ketone (8·6 g.) in ether with lithium aluminium deuteride (1·0 g.; Metal Hydrides Inc., 97% deuterium). The reaction product contained unchanged ketone, the bulk of which was removed by means of the Girard-P reagent; further purification was then effected by gas chromatography using 30% Apiezon L on Embacil. The yield was 1 g. The infrared spectrum showed absence of C=O. Impurities in the LiAlD$_4$ would not have yielded an alcohol.

The other deuterated alcohols were prepared similarly. The Girard-P reagent was used for purification of all the higher alcohols before their final fractionation. The analytical and kinetic procedures were those of Part IV.