255. *A Study of the Mechanism of Oxidation with Chromic Acid.*

By WILLIAM A. WATERS.

It has been found that oxygen is absorbed during the oxidation of many organic substances with chromium trioxide in glacial acetic acid, and it is concluded therefore that the oxidation mechanism involves an initial dehydrogenation process whereby free organic radicals are generated. The oxygen uptake is regarded as a diagnostic test for the presence of these transient radicals.

Substances showing this effect include hydrocarbons, alcohols, ethers, and ketones. The significance of the observations is discussed in relation to chemical structure.

In the course of an investigation of the mechanism of autoxidation of tetralin (Waters, *Trans. Faraday Soc.*, 1946, **42**, 184; Robertson and Waters, *ibid.*, p. 201), it was found that a rapid uptake of oxygen occurred immediately upon the addition of a small quantity of a solution of chromium trioxide in glacial acetic acid to tetralin at 76°, and that a similar catalytic effect was noticeable at room temperature. Since the autoxidation of tetralin can be depicted satisfactorily by the chain reaction sequence

$$R''CH\cdot + O_2 \longrightarrow R''CH\!-\!O\!-\!O\cdot \qquad \qquad \qquad \text{(i)}$$

$$R''CH\!-\!O\!-\!O\cdot + R''CH_2 \longrightarrow R''CH\!-\!O\!-\!O\!-\!H + R''CH\cdot \qquad \text{(ii)}$$

the initial product being tetralin hydroperoxide, it was suggested that chromium trioxide acted as an autoxidation chain starter by abstracting a hydrogen atom from tetralin and so forming a free hydrocarbon radical (of general type R''CH·) which, like free triphenylmethyl (compare Ziegler *et al.*, *Annalen*, 1933, **504**, 162; 1942, **551**, 213), can immediately combine with oxygen [reaction (i) above]; thus :

$$R''CH_2 + O\!\!=\!\!\overset{\text{vi}}{Cr}\!\!\diagdown\!\!\diagup^{O}_{O} \longrightarrow R''CH\cdot + H\!-\!O\!-\!\overset{\text{v}}{Cr}\!\!\diagdown\!\!\diagup^{O}_{O} \qquad \qquad \text{(iii)}$$

It was therefore of interest to see whether a similar uptake of oxygen occurred during the course of other oxidations with chromium trioxide. The results of a qualitative survey of a number of oxidations of organic compounds are given in the following Tables.

From these results it is evident that oxygen uptake during the course of oxidation of organic substances is a fairly regular phenomenon, and it can be concluded therefore that the normal mechanism of oxidation by chromium trioxide is that of hydrogen abstraction to give, as the initial product, a free neutral radical.

It must be pointed out, however, that a very sensitive method of detecting gas absorption has been used, and hence the efficiencies and the chain lengths of the subsequent autoxidation processes are often very low. On the other hand oxygen uptake can only occur with those substances which can form peroxides : the peroxides of many of the substances studied are as yet unknown, whilst some of them (*e.g.*, anthracene peroxide) may dissociate. Thus absence of gas absorption during oxidation with chromic acid does not necessarily indicate that there is any difference in reaction mechanism. In a few cases slight expansions have been observed. These almost invariably concern compounds from which carbon dioxide might well be one of the final oxidation products (*e.g.*, acetophenone).

In all the reactions studied it has been evident that oxygen is absorbed by the reacting system only whilst the reduction of the chromium trioxide is actually occurring. This is most marked with the primary and secondary alcohols which have been examined (Table II). The absorption of gas by these easily oxidisable compounds is immediate, but usually stops after 15—30 minutes, after which time it can be restarted at once

TABLE I.

Oxidation of CH_3, CH_2, *or* CH *Groups in Hydrocarbons and Analogous Substances.*

(a) *Substances oxidised at or below* 40°.

Compound.	Temp. used.	Result.
Toluene	40°	Slow O_2 absorption continuing over a long period.
p-Nitrotoluene	40	,, ,, ,, ,, ,, ,,
m-Xylene	40	Definite O_2 absorption.
p-Xylene	40	,, ,, ,,
Ethylbenzene	20	,, ,, ,,
*iso*Propylbenzene	20, 40	Some gas evolution for first hour followed by marked gas absorption.
Diphenylmethane	35	Definite O_2 absorption.
Triphenylmethane	20, 45	Slow oxidation combined with a *slight* evolution of gas.
Fluorene	15	Slow oxidation ⎱ with *slight* expansion.
	35	Rapid oxidation ⎰
Acenaphthene	20	Very definite O_2 absorption.
Anthracene	40	Rapid oxidation; gas uptake indefinite.
Phenanthrene	35	Slow O_2 uptake over long period.
Triphenylethylene	18	Marked O_2 absorption.
Decalin (mainly *trans*-)	20	Slow O_2 uptake over long period; slow oxidation.
*cyclo*Hexene	40	Rapid reaction with marked O_2 absorption; completed in 5 mins.
Oleic acid	40	Steady O_2 absorption during 2 hours; oxidation then completed.
Phenylacetic acid	40	Evolution of CO_2 masked observation.

(b) *Substances not oxidised at* 40°. Methyl*cyclo*hexane; ethyl*cyclo*hexane; 2 : 2 : 5-trimethylhexane; α-picoline; quinaldine; acetic acid; succinic acid; adipic acid.

TABLE II.

Oxidation of Alcohols and Ethers.

Compound.	Temp. used.	Result.
Benzyl alcohol	20°	Marked O_2 absorption which ceased when all CrO_3 had been reduced (30 mins.).
β-Phenylethyl alcohol	20	Marked O_2 absorption which ceased when all CrO_3 had been reduced (1 hour).
n-Butyl alcohol	20	Marked O_2 absorption which ceased when all CrO_3 had been reduced.
sec.-Butyl alcohol	20	,, ,, ,, ,, ,, ,, ,, ,,
n-Amyl alcohol	20	,, ,, ,, ,, ,, ,, ,,
*cyclo*Hexanol	20	Definite, but much slighter O_2 uptake.
Benzhydrol	20	O_2 uptake definite with carbinol in excess, but not with CrO_3 in excess; violet-red product.
Ethyl lactate	20	Definite O_2 absorption.
Triphenylcarbinol	40	Slow evolution of gas; slow oxidation (cf. triphenylmethane, Table I).
tert.-Butyl alcohol	40	Very little oxidation, but slight gas production.
Benzyl methyl ether	40	Marked O_2 absorption continuing over a long period.
n-Butyl ether	40	Definite O_2 absorption, continuing over a long period.
*iso*Propyl ether	20	Very slight reaction with some sign of O_2 uptake.
Phenetole	40	Very slow oxidation; no evident gas absorption.

TABLE III.

Oxidation of Ketones and Esters.

(a) *Substances oxidised at or below* 40°.

Compound.	Temp. used.	Result.
Methyl ethyl ketone	40°	Definite O_2 absorption, continuing over some hours.
Acetophenone	40	Gas evolution (? CO_2; cf. phenylacetic acid).
Menthone	40	Definite O_2 absorption over 2-hour period.
*cyclo*Hexanone	40	Slow O_2 absorption over long period.
α-Tetralone	40	Slight expansion.
Ethyl acetoacetate	40	Definite O_2 absorption; reaction almost completed in 30 mins.
Ethyl cinnamate	40	Very slow oxidation; slight expansion.

(b) *Substances not oxidised at* 40°. Camphor; ethyl malonate; ethyl phenylacetate; ethyl cyanoacetate; ethyl dichloroacetate; *n*-butyl benzoate; *sec.*-butyl benzoate; *cyclo*hexyl acetate.
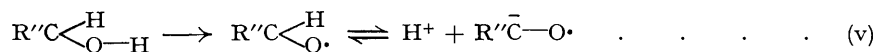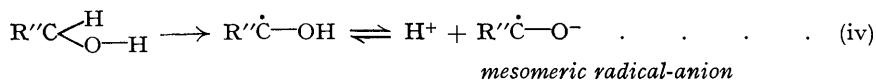
TABLE IV.

Other Substances.

(a) *Substances oxidised at* 40°. Benzyl cyanide. Slow O_2 uptake during some hours; oxidised. Piperidine (as acetate). Very slight O_2 absorption; very slight oxidation.
(b) *Substances not oxidised at* 40°. Benzylamine; di-*n*-butylamine (as their acetates).

by adding a little more chromium trioxide. The gas absorption is not therefore due to the production of an oxidation product of long free life, such as an aldehyde.
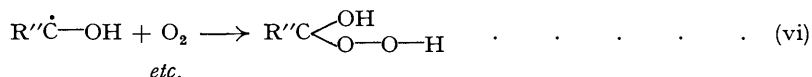
Most of the oxidisable substances listed in Table I are known to yield hydroperoxides by direct, or heavy-metal-catalysed autoxidation (for refs. see Waters, *Ann. Reports*, 1945, **42**, p. 131 *et seq.*), but it is interesting to note that oxygen uptake during oxidation is not confined to substances such as toluene, diphenylmethane, or

*cyclo*hexene which contain active methylene groups, but includes substances such as triphenylethylene and phenanthrene in which oxidation must affect a $>C\!\!=\!\!CH\!\!-$ group.

The results listed in Table II are of particular interest, since they show that the oxidation of both primary and secondary alcohols follows the dehydrogenation mechanism. For this two routes can be envisaged:

$$R''C\!\!<^{H}_{O-H} \longrightarrow R''\overset{\centerdot}{C}\!\!-\!\!OH \rightleftharpoons H^+ + R''\overset{\centerdot}{C}\!\!-\!\!O^- \qquad . \qquad . \qquad . \qquad . \qquad (iv)$$

<div align="center">mesomeric radical-anion</div>

$$R''C\!\!<^{H}_{O-H} \longrightarrow R''C\!\!<^{H}_{O\centerdot} \rightleftharpoons H^+ + R''\overset{-}{C}\!\!-\!\!O\centerdot \qquad . \qquad . \qquad . \qquad . \qquad (v)$$

of which only reaction (iv) can easily be conceived as leading to a hydroperoxide of known type, *viz.*

$$R''\overset{\centerdot}{C}\!\!-\!\!OH + O_2 \longrightarrow R''C\!\!<^{OH}_{O-O-H} \qquad . \qquad . \qquad . \qquad . \qquad (vi)$$

<div align="center">etc.</div>

The initial radical postulated in process (iv) has the electronic structure of a free ketyl radical (compare $Ph_2\overset{\centerdot}{C}\!\!-\!\!\overset{-}{O}Na^+$), but since the removal of a proton from either the radical of reaction (iv) or that of reaction (v) would yield a *mesomeric* radical-anion it may be difficult, if not impossible, to discriminate experimentally between the two processes. The first stage of reaction (v) should be possible with a tertiary alcohol, though the product, $R_3C\!\!-\!\!O\centerdot$, would not be expected to take up oxygen. Oxygen absorption has not, in fact, been noted in this case.

Some ethers absorb oxygen on oxidation, although they react much more slowly than do the corresponding alcohols; this must undoubtedly be due to attack at a C–H group, as in reaction (iv). In contrast, esters of these same alcohols with stable acids, such as benzoic or acetic acid, are resistant to oxidation.

Table III shows that oxygen is absorbed during the oxidation of some ketones. Since these are substances which are oxidised more easily than are the corresponding paraffinic hydrocarbons the reaction may perhaps be one in which the enolic form is concerned.

Whilst all the oxidations which have been studied in this investigation can consistently be interpreted as reactions involving dehydrogenation, it is significant that the ease of oxidation of an organic compound with chromium trioxide does not follow the sequence of ease of proton (H^+) removal. Thus ethyl malonate, ethyl phenylacetate, and ethyl cyanoacetate resist oxidation at 40°. Any oxidation of course involves electron abstraction, and the ease of removal of this electron is evidently the rate-controlling feature, since strongly electron-attracting groups in the organic molecule, such as carbethoxy or quaternary nitrogen, stabilise it. It does not follow, however, that ease of oxidation by homolytic separation of hydrogen atom (proton *plus* an electron) and ease of dissociation as an acid (proton release) should be converse processes, since other structural features have to be considered. For instance the oxidisability of benzyl cyanide, like that of toluene or of diphenylmethane, may be due to the possibility of formation of a mesomeric (*i.e.*, resonance stabilised) substituted benzyl radical. Again, the formation of a mesomeric radical can be invoked as the reason for the oxidisability of alcohols (see above).

Any homolytic dehydrogenation can be written as a one-stage process (*e.g.*, iii) or alternatively (cf. Weiss, *Trans. Faraday Soc.*, 1946, **42**, pp. 116, 122) as a two-stage process comprising

(*a*) Reversible ionisation of proton : $R''CH_2 \rightleftharpoons H^+ + (R''CH\!:)^-$

(*b*) Electron abstraction : $(R''CH\!:)^- + Ox \longrightarrow R''CH\centerdot + Red.$*
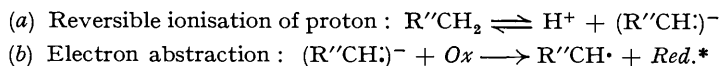
If this two-stage process of (*a*) followed by (*b*) were the true reaction sequence then facile proton release (*a*) should be conducive to oxidisability, for otherwise (*b*) could never occur. This does not accord with experimental fact. The hypothesis, for instance, would indicate that ethyl malonate should easily be oxidised, since with it stage (*a*) is easy, and so should be stage (*b*), since the anion, which occurs in ethyl sodiomalonate, is oxidised at room temperature by molecular iodine, which has a very low oxidation potential; *e.g.*

$$2CHNa(CO_2Et)_2 + I_2 \longrightarrow 2NaI + (EtO_2C)_2CH\!\!-\!\!CH(CO_2Et)_2$$
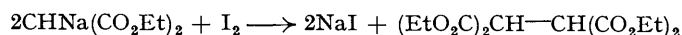
In order to formulate a bimolecular sequence in the reverse order

(*c*) $R''CH_2 + Ox \longrightarrow (R''CH_2)^+ + Red$

(*d*) $(R''CH_2)^+ \rightleftharpoons H^+ + (R''CH\centerdot)$
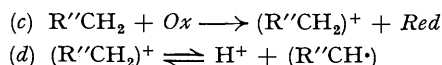
it is necessary to postulate the existence of radical-cations of simple paraffins in which one covalency has been converted into a single-electron bond. As yet such radical-cations have been encountered only in the "aminium salts," or in complex aromatic ring systems—both being structures derived from molecules in which all the valency electrons are not originally concerned in single bond (C–C or C–H) formation. The postulation of oxidation by one-stage removal of a hydrogen atom is thus both more satisfactory and more simple.

<div align="center">* Following standard nomenclature : $\epsilon + Oxidiser \rightleftharpoons Reducer.$</div>

Equation (iii) might be taken as suggesting that the reduction of chromium trioxide to a chromic salt involves the stepwise conversion of Cr^{VI} to Cr^{III} by three successive electron-accessions to the chromium atom. Whilst this view has already been put forward both by Luther (*Z. physikal. Chem.*, 1903, **46**, 777; *Z. anorg. Chem.*, 1907, **54**, 1) and by Wagner (*Z. physikal. Chem.*, 1924, **113**, 261; *Z. anorg. Chem.*, 1928, **168**, 265, 279) to explain certain features of the kinetics of oxidations involving aqueous chromic acid, it is not an essential part of the homolytic theory of oxidation by dehydrogenation. In connection with this earlier work, however, it is cogent to note that Wagner (*Z. anorg. Chem.*, 1928, **168**, 279) showed that, whilst acidified potassium dichromate does not react with potassium iodide in the presence of a sodium bicarbonate or sodium acetate buffer, some iodine is liberated if a reacting mixture of acidified chromic and oxalic acids is poured into a similar buffered solution. Reacting mixtures of chromic and lactic acids react even more noticeably with buffered iodide solutions. These curious observations can now be interpreted as being reactions in which short-lived organic radicals are concerned.

<div align="center">EXPERIMENTAL.</div>

A simple form of Barcroft's differential manometric apparatus was constructed by connecting the side-arms of two stoppered distilling flasks (*A* and *B*), of similar capacity (150 ml.), to the two limbs of a manometer filled with butyl phthalate, and fitting between the flasks a glass tap, by means of which the internal pressures could, if required, be equalised. The flasks were both immersed in a thermostat in which they were shaken periodically.

Into flask *A* were placed the substance to be investigated (usually 5 ml.) and glacial acetic acid (usually 20 ml.) previously stabilised by distillation from chromic acid. Into flask *B* were placed the same quantity of the substance and acetic acid (usually 25 ml.) taken from the same stock. A solution of pure chromium trioxide in the same acetic acid was also placed in the thermostat. When temperatures had equalised, and no manometric shift could be noted, chromium trioxide solution (5 ml.) was pipetted into flask *A*, so that the total volume of solvent in this flask was then the same as in flask *B*. Flask *A* was then stoppered, the air pressures in the flasks were equalised, and the interconnecting tap was closed.

Absorption of gas in *A* was easily observable as a progressive shift in the manometer level. From time to time the gas pressures in the flasks were momentarily equalised : a consistent pressure change over a period then indicated continuing gas absorption and not transient effects due to thermal irregularities, etc. " Definite oxygen absorption " in Tables I—III corresponds to a shift of manometric levels of over 2 cm. per hour. It was often very much more, and sometimes measured in centimetres per minute.

The observations with each substance were always carried out more than once, the reaction flasks being chosen at random. Particular care was taken in the purification of the substances. The purified acetic acid had no reducing action on chromium trioxide over a period of weeks. The organic substances were either distilled to constant b. p., with rejection of large head and tail fractions, or else crystallised repeatedly. In cases of doubt observations were repeated after further purification.