INTERNATIONAL JOURNAL OF CHEMICAL KINETICS, VOL. VIII, 205-214 (1976)

A Kinetic Study of the Oxidation of α-Hydroxy Acids and α-Hydroxy Ketones by Potassium Bromate

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Abstract

The oxidation of α -hydroxy acids and α -hydroxy ketones by Br(V) follows the rate-law

$$\frac{-d[Br(V)]}{dt} = k_2 [Br(V)] [substrate]$$

However, the former reaction exhibits a second-order dependence on hydrogen ion concentration while the latter reaction has a third-order dependence. A mechanism involving a slow formation of a bromate ester of the α -hydroxy acid followed by a fast decomposition is proposed. A rate-determining formation of a bromate ester from the conjugate acid of benzoin, followed by a rapid decomposition of the bromate ester, explains the kinetic data for the oxidation of benzoin.

During the course of our investigations of the kinetic aspects of the potassium bromate oxidation of secondary alcohols as reported earlier [1,2] we have subjected some α -hydroxy acids and a few α -hydroxy ketones to oxidation by Br(V). These acids bear a formal resemblance to propan-2-ol and α -phenyl ethyl alcohol in that they have an α -COOH in place of an α -CH₃, while α -hydroxy ketones bear a -CO-R group on the hydroxy-bearing carbon atom in place of an α -CH₃ or a -COOH group. It was therefore of interest to find out if the insensitivity to structural variations persisted in these instances also.

Experimental

Under identical conditions of acidity and solvent composition (acetic acidwater mixture) and in the temperature range of 45° to 65°C, the α -hydroxy acids and α -hydroxy ketones were subjected to oxidation by potassium bromate under pseudo-first-order conditions. The kinetics were followed by monitoring the concentration of bromate at regular intervals of time iodometrically to a starch end point. On account of the complications involved in the kinetics of bromate oxidation due to the production of bromide ions in solution, all the experiments were carried out in the presence of 0.01M mercuric acetate [1,2]. All data

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reported are average of at least two runs, and the velocity constants are reproducible within $\pm 3\%$.

The oxidation of α -hydroxy acids by Br(V) yields the corresponding aldehydes, while the corresponding diketones are obtained in the case of α -hydroxy ketones. The carbonyl products were identified by their corresponding DNP derivatives. Yields above 90% were obtained in all cases.

Results and Discussion

 α -Hydroxy acids like lactic, malic, mandelic, and *p*-bromo mandelic acids with a secondary hydroxyl group have been subjected to oxidation by Br(V), while in the case of α -hydroxy ketones substrates like acetoin, benzoin, and *p*-anisoin were used. Mandelic acid and benzoin have been taken as typical substrates for the kinetic study in the two groups. Under conditions of constant



Figure 1. First-order plots for hydroxy acids. A—lactic acid; B—mandelic acid; C—malic acid. Solvent = 50% HOAc, 50% H₂O (v/v); temperature = 55° C; [H₂SO₄] = 0.005M.

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acidity, the rate of oxidation of these two substrates by Br(V) follows the following rate law as in our earlier investigation [1,2] (Tables I and II):

(1)
$$\frac{-d[Br(V)]}{dt} = k_2 [Br(V)] [substrate]$$

where [substrate] denotes the hydroxy acid or hydroxy ketone (Figs. 1 and 2).

[BrO ₃ -]	$k_1 10^5 (\text{sec}^{-1})$	
(<i>M</i>)	Mandelic Acid	Benzoin
0.002158	8.25	1.14
0.003041	8.08	1.17
0.004014	8.28	1.05
0.005148	7.95	1.12
0.006175	8.40	1.16

TABLE I. Variation of bromate concentration in the oxidation of mandelic acid and benzoin.

 $[H_2SO_4] = 0.005M; [Hg(OAc)_2] = 0.01M;$ temperature = 55°C; solvent = 50% HOAc, 50% H₂O (v/v).



Figure 2. First-order plots for hydroxy ketones. A—acetoin; B—benzoin; C—para-anisoin. Solvent = 50% HOAc, 50% H₂O (v/v); temperature = 55° C; [H₂SO₄] = 0.005M.

	$k_{1}10^{5}$	k2104
	(sec ⁻¹)	$(1./mole \cdot sec)$
Mandelic acid		
0.1465	6.52	4.45
0.1953	7.95	4.07
0.2450	11.60	4.15
0.2964	12.50	4.23
Lactic acid		
0.1560	4.23	2.61
0.2008	5.02	2.49
0.2340	5.85	2.50
0.2501	6.28	2.50
Malic acid		
0.2038	1.07	5.28
0.2578	1.26	4.91
0.3074	1.56	5.08
0.3528	. 1.80	5.12
Acetoin		
0.03247	1.34	4.15
0.04212	1.70	4.05
0.05387	2.27	4.17
Benzoin		
0.02014	0.773	3.83
0.02517	0.994	3.95
0.03021	1.14	3.79
Para-anisoin		
0.03158	8.97	28.4
0.04237	12.5	29.3
0.05040	14.5	28.8

Table II.	Variation of substrate concentration in the bromate oxidation of
α -hydroxy acids and α -hydroxy ketones.	

 $[H_2SO_4] = 0.005M; [BrO_3^-] = 0.005M; [Hg(OAc)_2] = 0.01M; temperature = 55^{\circ}C; solvent = 50\% HOAc, 50\% H_2O (v/v).$

Influence of Solvent and Temperature

In order to study the effect of solvent polarity on the rate of oxidation of α -hydroxy acids and α -hydroxy ketones, the oxidations were carried out in varying percentages of acetic acid-water mixtures (Table III). The reaction rate is found to increase with the increasing percentage composition of the acetic acid in the solvent. In other words, the decreasing dielectric constant of the medium increases the rate of oxidation, broadly classifying the reaction as a positive ion-dipole reaction. Second-order rate constants obtained at one temperature are given for the various α -hydroxy acids and α -hydroxy ketones in Table IV.

HOAc-H ₂ O	$k_2 10^3$ (l./mole·sec)	
(% v/v)	Mandelic Acid	Benzoin
50-50	0.445	0.383
60-40	1.58	0.729
70-30	5.37	2.42

TABLE III. Variation of HOAc- H_2O mixture for the bromate oxidation of α -hydroxy acids and α -hydroxy ketones.

 $[BrO_3^-] = 0.005M; [H_2SO_4] = 0.005M; [Hg(OAc)_2] = 0.01M; temperature = 55^{\circ}C.$

Compound	$k_2 10^4$ (1./mole·sec)
Lactic acid	2.50
Malic acid	4.90
Mandelic acid	4.25
Para-bromo mandelic acid	4.98
Benzilic acid	4.92
Acetoin	4.15
Benzoin	3.83
Para-Anisoin	28.8

TABLE IV. Second-order rate constants for the bromate oxidation of of α -hydroxy acids and α -hydroxy ketones

 $[BrO_3^-] = 0.005M; [H_2SO_4] = 0.005M; [Hg(OAc)_2] = 0.01M; temperature = 55°C; solvent = 50\% HOAc, 50\% H_2O (v/v).$

Structural Effects in the Br(V) Oxidation

Para-bromo mandelic acid and para-anisoin were subjected to oxidation to study the structural influences on the rate of oxidation of the two substrates by Br(V). In addition lactic and malic acids and also acetoin have been subjected to oxidation under identical conditions.

Effect of Added Hg(II) Ions

It is proven beyond doubt that the changes in the concentration of added mercuric acetate over a fourfold range produce no change in the rate constant in these studies as in the case of aliphatic secondary alcohols [2]. However, it is found that at concentrations below 0.01M the [Hg(II)] ions are not sufficient to keep back all the bromide produced, which will lead to concurrent oxidation of the substrate in the system by bromine.

Acidity Dependence

The effect of varying acid concentrations on the reaction rate was studied in the range of 0.5M to 2.0M for the oxidation of mandelic acid and benzoin. The

rate of oxidation shows a second-order dependence on hydrogen ion concentration in the case of mandelic acid, but a third order dependence on hydrogen ion concentration in the case of benzoin, which is indicated in the slopes of the plot of log k_2 versus log [H⁺] (Table V, Fig. 3).

$[H_2 SO_4] \\ (M)$	$k_2 10^3$ (l./mole · sec)	
	[Benzoin] ^a	[Mandelic Acid] ^b
0.5	2.08	3.58
0.75		7,23
1.00	10.00	12.50
1.25		20.00
1.50	34.11	32.3
1.75		50.9
2.00	101	—

TABLE V. Variation of acidity in the bromate oxidation of mandelic acid and benzoin.

 $[BrO_3^-] = 0.005M; [Hg(OAc)_2] = 0.01M; temperature = 30^{\circ}C.$

^a 0.05*M*; solvent = 50% HOAc, 50% H₂O (v/v).

^b 0.15*M*; solvent = 20% HOAc, 80% H₂O (v/v).

Mechanism of Br(V) Oxidation of α -Hydroxy Acids

Based on the experimental findings, the following mechanism may be proposed for the bromate oxidation of α -hydroxy acids, as proposed for aliphatic secondary alcohols [2], aromatic secondary alcohols [3] and cyclanols [4]:

(2)
$$\begin{array}{c} H & H \\ R - C - OH + H_2 BrO_3 \xrightarrow{\text{slow}} R - C - OBrO_2 H + H_2 O \\ COOH & COOH \end{array}$$

It is observed herein again that, in spite of considerable variations in structure, these substrates are oxidized at nearly the same rate (although lactic acid alone gets oxidized at a slower rate). There is a formal analogy between this proposed mechanism and the mechanism proposed for chromic acid oxidation of alcohols [5,6]. The structural insensitivity observed in the hydroxy acid oxidation by Br(V) rules out the possibility of the bromate ester decomposition being the rate-determining step. This step involves the cleavage of a strong C-H bond and is bound to be influenced by structural changes in the hydroxy acid, as was seen in chromic acid oxidation [7] or in the oxidation with bromine [8]. The assumption of the bromate ester formation being the slow step would explain the observed



Figure 3. Order plot with respect to $[H^+]$ in the bromate oxidation of Benzoin. Solvent = 50% HOAc, 50% H₂O (v/v); temperature = 30°C.

insensitivity to structural influences. Inorganic esterification reactions of this type are known to be not influenced by structural variations in alcohol moiety [9-11].

The bromate ester formed in the first step may also react with the proximate carboxylic acid group to form a cyclic ester which may subsequently decompose to give the products



An analogy for the above cyclic ester could be the cyclic chromate ester or a Pb(IV) ester, which vicinal diols are capable of forming with chromic acid and

Pb(IV) acetate, respectively [12]. In such a case again, the formation of the monoester is most likely to be the slow step, followed by its rapid decomposition.

Although the bromate ester was considered to be formed in the above mechanistic picture by a nucleophilic attack by the alcoholic hydroxyl at the bromine atom of the H_2BrO_3 molecule, the alternative mode of attack by the carboxyl group cannot be ruled out.

(5)
$$\begin{array}{ccc} H & H \\ H & H \\ -C & -COOH + H_2BrO_3 \xrightarrow{slow} R - C - C = O \\ OH & HO & O - BrO_2H \\ \end{array}$$
(6)
$$\begin{array}{ccc} H & O \\ R - C & -C \\ O & -BrO_2H \\ H & B \end{array}$$

Such an ester has been conceived in the reaction between bromine and oxalic acid, which is considered to proceed as follows [13]:



Although there is a formal analogy between the mechanism proposed herein and the chromate ester mechanism for the oxidation of alcohols by Cr(VI) oxide, there are several important differences between the two processes. Chromic acid oxidations are known to exhibit a pronounced kinetic isotope effect $(k_H/k_D = 7$ for the oxidation of isopropyl alcohol) and a negative *rho* has consistently been obtained for the oxidation of several substituted alcohol systems. These establish unequivocally that the decomposition of the chromate ester constitutes the slow step. But the oxidation of alcohols by Br(V) is characterized by the absence of any substituent effect and any kinetic isotope effect [2].

One way of demonstrating that in the present system also the decomposition of the ester is a fast one, is to study the oxidation of a hydroxy acid like benzilic acid. One would predict, according to the proposed mechanism, almost identical

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rates for the oxidation of benzilic acid and mandelic acid. This is exactly what is observed (Table IV).

Mechanism of Br(V) Oxidation of α -Hydroxy Ketones

There seems to be little variation in the reactivity of the two keto alcohols acetoin and benzoin, although *p*-anisoin is oxidized about seven times faster than benzoin (Table IV). A mechanism for the oxidation of benzoin, analogous to that proposed for alcohols, will be the following:

(9) Ph-CHOH-CO-Ph + H₂⁺BrO₃
$$\xrightarrow{\text{slow}}$$
 Ph-CO-CO-Ph
 $O-BrO_2H$
(10) Ph-C-CO-Ph
 $O-BrO_2H$
 $H \longrightarrow B$
 $Ph-CO-CO-Ph + BH^+$
 $O-BrO_2H$
 $H \longrightarrow B$
 H

However, while the alcohol bromate reactions followed a second-order dependence on the hydrogen ion concentration, the benzoin bromate reaction exhibits a third-order dependence on $[H^+]$. This dependence can be accommodated in the above mechanistic scheme if it is assumed that the Br(V) reacts with the conjugate acid of benzoin.

(11)
$$C_6H_5$$
--CHOH--CO--C $_6H_5$ + H⁺ $\stackrel{K}{\longleftrightarrow}$ C_6H_5 --CHOH--C--C $_6H_5$
(12) C_6H_5 --CHOH--C--C $_6H_5$ + H_2BrO_3 $\stackrel{k \text{ slow}}{\longleftarrow}$ C_6H_5 --C---C--C $_6H_5$
 O_H

(13)
$$C_6H_5 \longrightarrow C_6H_5$$

 $O OH$
 $G OH$

Such a formation would be consistent with the rate law

$$\frac{-d[\operatorname{Br}(V)]}{dt} = k \text{ [benzoin H^+] [H_2 \operatorname{BrO}_3]}$$
$$= Kk \text{ [benzoin] [H^+] [H_2 \operatorname{BrO}_3]}$$
$$= Kk \text{ [benzoin] [Br(V)] [H^+]^3}$$

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The increase in rate with para-anisoin could be traced to an easier formation of the conjugate acid in eq. (11) because of a greater resonance stabilization from the benzoyl end and also an easier formation of the ester in eq. (12) due to the +M effect of the methoxy group in the benzyl half of the molecule.

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Received January 29, 1975 Revised July 21, 1975