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Carbon-13 Isotope Fractionation in the Oxidation of Acetic Acid of Natural Isotopic Composition with Homogeneous Solution of Chromic Anhydride in Orthophosphoric Acid

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^{13}C-isotope fractionation in the oxidation of acetic acid, (AA), of natural isotopic composition with homogeneous solution of chromic anhydride, CrO_3, in 85% orthophosphoric acid has been investigated in the temperature interval 30–90°C and the measured ^{13}C fractionation factors, located in the range 1.021–1.016, have been compared with the earlier kinetic isotope effect (KIE) data for the oxidation of acetic acids labelled with carbon-14 in the carboxyl and in the methyl groups. A comparison of the ^{13}C KIE found to be of 1.026 for oxidation of $^{13}CH_3COOH$ at 51°C with the ^{13}C KIE of 1.029 ± 0.002 at 45°C and of 1.0266 at 21°C observed in the oxidation of formic acid of natural isotopic composition in the gas phase and in liquid phase oxidation respectively has been done also. These comparisons of the rate isotope effects, k_{12}/k_{13}, for acetic acid and for formic acid oxidation led the authors to conclusion that the cleavage of carbon to hydrogen bond in acetic acid is the rate determining step and the oxidation of AA proceeds with complete loss of the $^{13}C–^{1}H$ bond in the activated state. Two oxidation schemes, both involving the rupture of the $^{13}C–^{1}H$ bond in the TS have been proposed to rationalise the methyl- and carboxyl-carbon isotope effects in oxidation of AA with chromic acid-orthophosphoric acid solution. It has been shown also that the resistance of AA towards oxidation with Cr(VI) is caused by the higher by 5–6 kcal/mol activation energy relative to the oxidation of the methylene groups of the aliphatic carboxylic acids similarly as it has been observed in the oxidation of methyl group of acetate with alkaline permanganate.

Key words: acetic acid, oxidation, chromic anhydride, orthophosphoric acid, kinetics, carbon-13 isotope fractionation, isotope effects

Acetic acid (AA) is considered to be highly inert in degradations of aliphatic carboxylic acids with chromium trioxide in acidic media and together with carbon dioxide serves to establish the length of aliphatic chain in analytical organic procedures. AA and its water solutions (up to 95%) have been frequently used as the solvent in studies of the mechanisms of oxidation of alpha-hydroxycarboxylic acids and hydrocarbons (even aliphatic hydrocarbons) by chromic acid. Rather strong ("severe") oxidation conditions of Van Slyke-Folch wet combustion method [1] are applied to oxidise AcOH. Even in such extreme reactive medium, which contained chromic anhydride, oleum, orthophosphoric acid, besides iodine oxides, the ^{14}C and ^{13}C isotope fractionation in oxidation of AA has been observed [2–5] and the oxidation had to be carried out up to completion to avoid changes of $^{14}C/^{12}C$ and $^{13}C/^{12}C$ ratios in carbon dioxide obtained at partial oxidation of acetic acid with respect to the initial carbon isotope ratios of acetic acid. After preliminary study of the carbon and hydrogen isotopes fractionation in the oxidation of propionic acid with homogeneous solutions of chromium trioxide in 85% orthophosphoric acid [6–8] we carried out the short series of experiments aimed at the assessment of the kinetics and of the ^{13}C KIE's in the oxidation of AcOH of natural isotopic composition with $CrO_3/H_3PO_4/H_2O$ solution in the 30–90°C temperature interval. The calculation of the ^{13}C fractionation factors in the case of oxidation of two carbon acetic acid of natural isotopic composition is somewhat more complicated task than the calculation of ^{13}C fractionation and mass spectrometric analysis of the oxidation of formic acid, monocarbon compound [9,10]. Nevertheless, the homogeneous solution of chromic anhydride in 85% orthophosphoric acid is much simpler oxidising medium than the Van Slyke-Folch oxidising mixture [1–5] and this should facilitate the analysis and interpretation of mass spectrometric and kinetic data.

EXPERIMENTAL

About 3.2 mmoles of frozen acetic acid (p.a., 80%, produced by P.O.Ch. Gliwice) has been mixed under vacuum with 3 cc of homogeneous solution of 5.05 mmoles of chromium(VI) oxide (Merck reagent 99.9%) in 85% H_3PO_4 (p.a.) and the reaction vessel transferred to ultra thermostat adjusted to temperatures indicated in column (1) of Table 1 for present reaction times. Carbon dioxide extracted from reaction vessel was purified by cryogenic methods and sealed with flame under vacuum in standard glass tubes for mass spectrometric determinations. The delta(PDB)($^{13}C/^{12}C$) values listed in column (3) have been determined with Europa Scientific 20–20 mass spectrometer with ANCA-TG preparative modul operating in the Reactor Center of the J. Stefan Institute of Ljubljana. They are related with the carbon isotope ratios, R($^{13}C/^{12}C$), presented in column (4) of Table 1 with equation: $\delta_{(‰)} = [(R_{sample}/R_{standard}) - 1] \cdot 1000$. The ratios of isotopic ratios, $R(^{13}C/^{12}C)_{so}/R(^{13}C/^{12}C)_{pf}$, presented in column (5), indicating that acetic acid molecules containing carbon-13 react at slower rate than light AA molecules containing carbon-12 only, have been used to calculate the ratios of specific rate constants (k_{-1}/k_{-2}) and (k_{-1}/k_{-3}) presented in columns (4)–(6) (a and b respectively) of Table 2 using the equation (1) [5]:

$$\frac{k_{-1}}{k_{-2}} = \frac{\left[\dfrac{1 + Q_t\dfrac{k_{-3}}{k_{-2}}}{1+\dfrac{k_{-3}}{k_{-2}}}\right]\ln(1-f)}{\ln\left[1 - \dfrac{(1+Q_0)\dfrac{R_f}{R_0}f}{1+\dfrac{k_{-3}}{k_{-2}}}\right]} \qquad (1)$$

where: $Q = (^{13}CH_3\text{-}^{12}COOH/^{12}CH_3\text{-}^{13}COOH)$, R_f and R_0 are the ($^{13}CO_2/^{12}CO_2$) ratios of carbon dioxide at time "t" or at the degree of reaction "f "and at complete combustion of the original acetic acid respectively, $R_{0,\,k-1}$ is the specific rate constant for oxidation of $^{12}CH_3{}^{12}COOH$ (eq. 2), k_{-2} that for oxidation of $^{12}CH_3{}^{13}COOH$ (eq. 3), and k_{-3} that for $^{13}CH_3{}^{12}COOH$ (eq. 4).

$$^{12}CH_3{}^{12}COOH \xrightarrow{k_{-1}} 2\ ^{12}CO_2 \qquad (2)$$

$$^{12}CH_3{}^{13}COOH \xrightarrow{k_{-2}} {}^{12}CO_2 + {}^{13}CO_2 \qquad (3)$$

$$^{13}CH_3{}^{12}COOH \xrightarrow{k_{-3}} {}^{13}CO_2 + {}^{12}CO_2 \qquad (4)$$

The second order rate constants presented in column (6) of Table 1 have been calculated using equation (5) corresponding to the stoichiometric equation (6), where “a” and “b” are the initial concentrations of acetic acid and chromic anhydride respectively, “x” is the concentration of acetic acid that has reacted, (8x/3) is the concentration of CrO_3 that has reacted at the same time t, k is the second order rate constant expressed in $dm^3\ mol^{-1}\ s^{-1}$.

$$\ln \frac{1-\frac{x}{a}}{1-\frac{8x}{3b}} = \left[\frac{8a}{3} - b\right] kt \qquad (5)$$

$$3CH_3COOH + 8CrO_3/85\%H_3PO_4 \longrightarrow 6CO_2 + 8CrPO_4 + 18H_2O \qquad (6)$$

RESULTS AND DISCUSSION

The kinetic and C-13 results are presented in Table 1 and Table 2.The second order rate constants for oxidation of acetic acid with chromium trioxide in 85% orthophosphoric acid given in column (6) of Table 1 are by 2–3 order of magnitude smaller that the rate constants for propionic acid oxidations [6] but they are accessible for determinations even at 30°C. Their Arrhenius plot (equations 7 and 8)

$$\ln(k) = 18.3566 - 11.004/T \qquad \text{correl. coef.} = 0.9991 \qquad (7)$$

$$k = 9.38 \cdot 10^7\ e^{-21.9/RT}\ dm^3\ mol^{-1}\ s^{-1} \qquad (8)$$

indicates that the resistance of acetic acid towards oxidation is caused mainly by higher by about 5–6 kcal/mol activation energy which is compensated only partly by the higher preexponential factor similarly as it has been observed in oxidation of methyl group of acetate with alkaline permanganate [7]. The carbon-13 isotope effect data presented in Table 2 have been calculated by taking a value of 0.988 ±.004 for ^{13}C (k_{-3}/k_{-2}). It has been assumed that the per cent ^{14}C kinetic isotope effects for Van Slyke oxidation of $CH_3{}^{14}COOH$ and $^{14}CH_3COOH$ isotopomers [4] are twice the corresponding ^{13}C per cent isotope effects. The assessed per cent (k_{-1}/k_{-2}) ^{13}C KIE is about 1.03 ± 0.2 at 90°C. The per cent (k_{-1}/k_{-3}) ^{13}C KIE for $^{13}CH_3{}^{12}COOH$ oxidation

Table 1. Carbon-13 fractionation in oxidation of 3.2244 mmoles of acetic acid (AA) with 3 cc of homogeneous solution of chromic anhydride (5.0506 mmoles) in 85% orthophosphoric acid.

Sample No/Reaction Temp., [°C]	Degree, f = x/a, of oxidation acetic acid	δ(PDB)(^{13}C/^{12}C) of extracted carbon dioxide	R(^{13}C/^{12}C) carbon isotope ratio	R_{so}/R_{pf} ratios	Rate constant "k"**
(1)	(2)	(3)	(4)	(5)	(6)
A-1/31.8	0.00305	–41.86(pf)* –21.605(so)	0.0107668(pf) 0.0109944(so)	1.02114	$2.193 \cdot 10^{-8}$
A-2/51.0	0.0143	–40.41(pf)	0.00107831(pf) 0.0109951(so)	1.01966	$1.473 \cdot 10^{-7}$
A-3/90.1	0.0840	–36.75(pf)	0.0108242(pf)	1.01607	$6.914 \cdot 10^{-6}$
Van Slyke-Folch wet oxidation of unreacted acetic acid (cont.) with large excess of chromic anhydride					
A-4/90.1	0.9236	–20.98(pf)	0.011001(pf)		
A-5/90	1.0	–6.18(pf)	0.0111678(pf)		

*/(pf) corresponds to product carbon dioxide; (so) corresponds to C in substrate at the beginning of sample collection for analysis.

**/Rate constants k in dm^3 mol^{-1} s^{-1} calculated with equation:

$$\ln \frac{1-\frac{x}{a}}{1-\frac{8x}{3b}} = \left[\frac{8a}{3} - b\right] kt$$

where a and b denote the concentrations of AcOH and CrO_3, correspondingly.

Table 2. Carbon-13 isotope effects in the oxidation of acetic acid of natural isotopic composition with homogeneous solution of chromic anhydride in 85% orthophosphoric acid.

Reaction Temp. [°C]	Degree of oxidation f = x/a	R_{so}/R_{pf} ratio*	^{13}C KIE's for carboxylic (C-1) carbon (a), and for methyl (C-2) carbon (b)**					
			(4)		(5)		(6)	
(1)	(2)	(3)	(a)	(b)	(a)	(b)	(a)	(b)
90.1	0.0840	1.01607	1.01037	1.02275	1.01018	1.02255	1.010499	1.02288
51.0	0.0143	1.01966	1.01359	1.02600	1.01354	1.02595	1.01362	1.02604
31.8	0.00305	1.02114	1.01499	1.02742	1.01496	1.02739	1.01500	1.02744

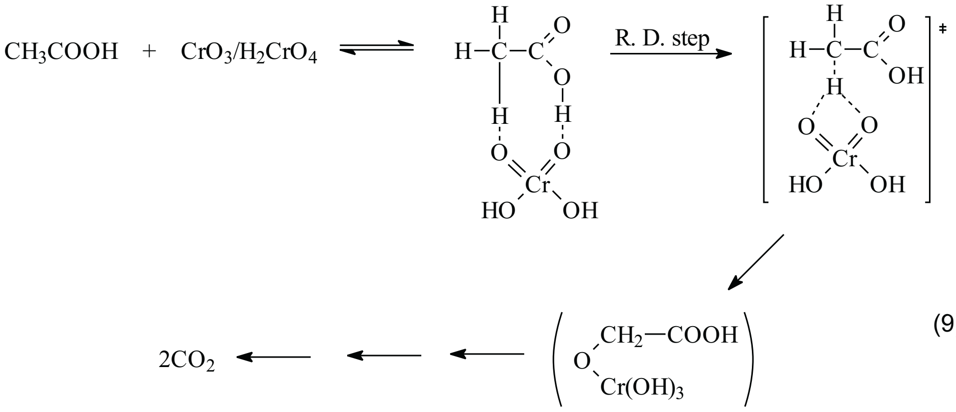
*/R_{so} corresponds to the initial carbon isotope ratio, $R(^{13}C/^{12}C)_{so}$, of acetic acid used in the oxidation experiments, R_{pf} corresponds to product carbon dioxide
**/(4)–(5)–(6) calculated with the use of equation:

$$\frac{k_{-1}}{k_{-2}} = \frac{\left[\dfrac{1 + Q_t \dfrac{k_{-3}}{k_{-2}}}{1 + \dfrac{k_{-3}}{k_{-2}}}\right] \ln(1 - f)}{\ln\left[1 - \dfrac{(1 + Q_0)\dfrac{R_f}{R_0} f}{1 + \dfrac{k_{-3}}{k_{-2}}}\right]}$$

explained in the text, by taking $k_{-3}/k_{-2} = 0.9879$ and assuming Q = 1.000 (4), Q = 1.0074 (5), and $Q = (1.005)^{-1}$ (6) respectively.

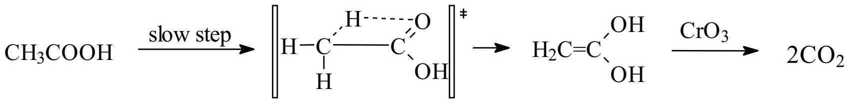
with CrO_3/H_3PO_4 solution is assessed to be $2.27 \pm 0.02\%$ at 90°C. These per cent ^{13}C KIE's increased to 1.5% and to 2.7% respectively with decrease of the oxidation temperature to 32°C but there are no ^{14}C KIE data for low temperature oxidation of ^{14}C-labelled acetic acid molecules. The assessed ^{13}C KIE's do not depend significantly on the changes of the value of the ratio Q (defined in eq.1) from 1.0074 to 0.995. In biological samples 1.2% changes of ^{13}C contents corresponding to carbons of carboxylic and of CH_n groups are observed [11,12]. The ^{13}C KIE of 1.029 ± 0.002 was observed in the gas phase oxidation of formic acid with bromine [9]. This value is very close to ^{13}C KIE equal 1.026 assessed in our experiment corresponding to oxidation of $^{13}CH_3COOH$ at 51°C. Thus it is logical to assume that the cleavage of the carbon-to-hydrogen bond is the rate controlling step in the oxidation of acetic acid. In the oxidation of formic acid with uranium peroxide involving also the C–H bond rupture the (k_{12}/k_{13}) ^{13}C KIE, equal 1.018/at 121°C, increased to 1.022/at 50°C and then to 1.0266/at 21°C. The above mechanistic conclusion require therefore to classify the measured ^{14}C KIE in the oxidation of $CH_3{}^{14}COOH$ and the corresponding ^{13}C KIE as the secondary KIE's. Secondary ^{14}C KIE in the oxidation of $^{14}CH_3CH_2COONa$ with permanganate at 100°C was of $0.6 \pm 0.3\%$ only [7]. ^{14}C KIE in the oxidation of $CH_3{}^{14}COOH$ with CrO_3 in H_3PO_4/H_2SO_4 was of $1.7 \pm 0.5\%$. The corresponding secondary ^{13}C KIE in the oxidation of $CH_3{}^{13}COOH$ should be of (0.5–0.8)%. We propose the oxidation scheme (9) involving the rupture of the ^{13}C–H bond in the transition state as consistent with carbon-13 isotope effect data present in Table 2.

The slight changes of the bonding at the carboxyl carbon, caused by protonation of the



(9)

carboxylic group, might increase the secondary ^{14}C KIE and the related secondary ^{13}C KIE resulting the cumulative ^{13}C fractionation, k/k^x, of 1.016–1.021 listed in column (5) of Table 1 for temperature interval 90–30°C. The rate determining isotopic carbon to hydrogen bond splitting is in agreement also with the eventual internal hydrogen transfer preceding the enol formation (eq.10), which undergoes then fast oxidation involving the attack of Cr(VI) at the double bond formed as the result of enolization. The last internal process may be partly responsible also for the relatively large secondary ^{14}C KIE observed in the oxidation of $CH_3{}^{14}COOH$ found to be greater than the ^{14}C secondary isotope effect of 0.6% ($k_{12}/k_{14} = 1.006 \pm 0.003$ at 100°C) observed in the permanganate oxidation of beta-^{14}C-labelled propionate, $^{14}CH_3CH_2COO^-$ [7].



(10)

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