The neutral hydrolysis of methyl acetate — Part 1. Kinetic experiments

Yih-Huang Hsieh, Noham Weinberg, and Saul Wolfe

Abstract: The neutral hydrolysis of methyl acetate and catalysis of the reaction by the acetic acid product have been studied in the temperature range 90–110 °C. Extrapolated to 25 °C, the rate constants are $0.17 \times 10^{-8} \text{ s}^{-1}$ for the uncatalyzed reaction and $1.4 \times 10^{-4} \text{ (mol/L)}^{-1}\text{s}^{-1}$ for the catalyzed reaction. The acid catalysis is specific not general: at 90 °C the rate constants for hydrochloric acid catalysis and catalysis by ionized acetic acid are the same as the rate constant, $k_{\rm H} = 1.4 \times 10^{-2} \text{ (mol/L)}^{-1}\text{s}^{-1}$, determined in the neutral reaction.

Key words: specific acid catalysis, general acid catalysis, cooperative mechanism.

Résumé : Opérant à des températures allant de 90 à 110 °C, on a étudié l'hydrolyse neutre de l'acétate de méthyle et la catalyse de la réaction par l'acide acétique produit. Extrapolées à 25 °C, les constantes de vitesse sont égales à 0,17 x 10⁻⁸ s⁻¹ pour la réaction non catalysée et à 1,4 x 10⁻⁴ (mol/L)⁻¹ s⁻¹ pour la réaction catalysée. La catalyse acide n'est pas générale; à 90 °C, les constantes de vitesse pour la catalyse par l'acide chlorhydrique et pour la catalyse par l'acide acétique ionisé sont les mêmes que la constante de vitesse, $k_{\rm H} = 1,4 \times 10^{-2} (mol/L)^{-1} \rm s^{-1}$, déterminée pour la réaction en milieu neutre.

Mots-clés : catalyse acide spécifique, catalyse acide générale, mécanisme coopératif.

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Introduction

In recent publications,^{1–4} we have reported that the neutral, acetic acid-catalyzed and 2-hydroxypyridine(2-pyridone) catalyzed aqueous hydrations of carbonyl compounds are paradigms of cooperativity,^{5,6} by which we mean that C–O bond formation and proton transfer to oxygen take place in each case through an uncharged bridge of solvent and (or) catalyst molecules. This mechanism provides a preferred neutral alternative to multistep ionic processes in which charged intermediates would be undergoing continuous solvation and desolvation as they appear and disappear.⁵

The series of studies of which the present article is Part 1 was undertaken to determine if a neutral ester hydrolysis, whether via a one-step (Scheme 1) or two-step (Scheme 2) pathway, can also proceed via a cooperative mechanism.

The issue is complicated experimentally because neutral ester hydrolysis produces a carboxylic acid, which can affect kinetics by a combination of general and specific acid catalysis, i.e.,

$$[1] k_{\rm obs} = k_{\rm o} + k_{\rm HA}[{\rm HA}] + k_{\rm H}[{\rm H}^+]$$

where k_0 is the rate constant of the neutral reaction of interest, k_{HA} is the rate constant resulting from general acid cata-

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lysis by the product, and $k_{\rm H}$ is the rate constant resulting from specific acid catalysis by the product. Our interest is in $k_{\rm o}$, but $k_{\rm HA}$, if important, may also involve cooperativity. The specific objective of the present work is to obtain the experimental values of $k_{\rm o}$ and $k_{\rm HA}$ or $k_{\rm H}$ for the hydrolysis of methyl acetate in water solvent, for comparison with the values of $k_{\rm o}$ and $k_{\rm HA}$ calculated⁷ assuming cooperative mechanisms. Prior to this work, it had been reported that ethyl acetate exhibits $k_{\rm o} = 2.47 \times 10^{-10} \, {\rm s}^{-1} \, {\rm s}$ and ethyl formate exhibits $k_{\rm o} = 5.0 \times 10^{-6} \, {\rm s}^{-1}$ at 298 K.⁹

Experimental

Materials

Methyl acetate was dried over anhyd. copper sulfate, distilled under nitrogen, and stored over 4 Å molecular sieves. $H_2^{16}O$ was obtained from an Easypure UV/UF ultrapure water system. Acetic acid (1.000 mol/L, Aldrich) was standardized by titration with 0.1 mol/L sodium hydroxide.

Neutral hydrolyses

Experiments were performed in sealed tubes, which had been washed sequentially with chromic acid and water, and dried at 110 °C. During reactions, all tubes were completely immersed in a stirred, temperature-controlled oil bath for the required time. Temperature control was achieved with a Model 51 Thermotronic temperature controller. To stop reactions, tubes were removed, cooled in ice, and maintained at -20 °C. Kinetics were monitored by measurement of the integrals of the methoxy peaks of methyl acetate and methanol. For reactions at 90 ± 0.5 °C, methyl acetate (4.80 mL, 4.473 g, 60.3 mmol) was added to water (60.0 mL) to give a 1.00 mol/L solution, and this solution was transferred to 60×1 cm tubes, which were sealed and frozen until used. For reactions at 100 ± 0.8 °C and 110 ± 0.8 °C, methyl acetate (3.60 mL, 3.355 g, 45.3 mmol) was added to water 540

Scheme 1.



(45.0 mL) to give a 1.00 mol/L solution, and this solution was transferred to two sets of 45×1 cm tubes, which were sealed and frozen until used.

Catalysis by hydrochloric acid at 90 °C

0.93 mmol/L HCl

Methyl acetate (2.40 mL, 2.239 g, 30.2 mmol) and hydrochloric acid (0.30 mL, 0.100 mol/L) were added to water (30.0 mL) to give a solution (1.00 mol/L in methyl acetate and 0.93 mmol/L in hydrochloric acid). This solution was transferred to 33×1 cm tubes, which were sealed and frozen until needed.

4.8 mmol/L HCl

Methyl acetate (1.60 mL, 1.491 g, 20.1 mmol) and hydrochloric acid (1.0 mL, 0.100 mol/L) were added to water (20.0 mL) to give a solution (1.00 mol/L in methyl acetate and 4.8 mmol/L in hydrochloric acid). This solution was transferred to 22×1 cm tubes, which were sealed and frozen until needed.

6.5 mmol/L HCl

Methyl acetate (2.40 mL, 2.239 g, 30.2 mmol) and hydrochloric acid (2.1 mL, 0.100 mol/L) were added to water (30.0 mL) to give a solution (1.00 mol/L in methyl acetate and 6.5 mmol/L in hydrochloric acid), and this solution was transferred to 33×1 cm tubes, which were sealed and frozen until needed.

9.1 mmol/L HCl

Methyl acetate (2.40 mL, 2.239 g, 30.2 mmol) and hydrochloric acid (3.0 mL, 0.100 mol/L) were added to water (30.0 mL) to give a solution (1.00 mol/L in methyl acetate and 9.1 mmol/L in hydrochloric acid). This solution was transferred to 33×1 cm tubes, which were sealed and frozen until needed.

Catalysis by acetic acid at 90 °C

Methyl acetate (0.168 mL, 0.1562 g, 2.11 mmol) was added to acetic acid (21.0 mL, 1.00 mol/L) to give a solution (0.10 mol/L in methyl acetate and 1.00 mol/L in acetic acid). This solution was transferred to 21×1 cm tubes, which were sealed and frozen until needed.

Analysis of kinetic data

Kinetic data for the neutral hydrolyses were treated using Scheme 3 and eq. [2],

Scheme 2.

$$\overrightarrow{\mathbf{R}'\mathrm{OH}} + \overrightarrow{\mathbf{R}'\mathrm{OH}} + (n-1)\mathrm{H}_2\mathrm{O}$$

[2]
$$v = -\frac{dC_{\rm E}}{dt} = k_1 C_{\rm E} - k_{-1} C_{\rm A} C_{\rm B}$$

where $C_{\rm E}$, $C_{\rm A}$, and $C_{\rm B}$ are the concentrations of ester, acetic acid, and methanol. Since the process is catalyzed by the product,

$$[3] k_1 = k_1^0 + k_1^{\rm H} [{\rm H}^+]$$

and

$$[4] k_{-1} = k_{-1}^0 + k_{-1}^{\rm H} [{\rm H}^+]$$

where k_1^0 and k_{-1}^0 are the neutral rate constants and k_1^H and k_{-1}^H are the specific acid-catalyzed rate constants of the forward and reverse reactions. The contribution of k_{-1}^0 can be neglected because in the initial stages of the reaction there is no reverse reaction, and as hydrolysis proceeds, the acid-catalyzed reverse reaction becomes dominant. Since C_A and C_B are stoichiometrically related to C_E and its initial value C_{E0} , eq. [2] becomes

[5]
$$v = -\frac{\mathrm{d}C_{\mathrm{E}}}{\mathrm{d}t} = (k_1^0 + k_1^{\mathrm{H}})C_{\mathrm{E}} - k_{-1}^{\mathrm{H}}(C_{\mathrm{E}_0} - C_{\mathrm{E}})^2$$

The required specific acid concentration [H⁺] can be found from eq. [6],

[6]
$$[H^+] = \frac{-(H_o + K_a) + \sqrt{(H_o + K_a)^2 + 4(C_{E_0} - C_E)K_a}}{2}$$

where H_0 is 10⁻⁷ mol/L and K_a is the dissociation constant of acetic acid, $1.7 \pm 0.2 \times 10^{-5.10}$

The Verlet algorithm¹¹ was employed to integrate eq. [5] with a time step δt for a given set of the parameters k_1^0 , k_{-1}^0 , and k_{-1}^H

[7]
$$C_{\mathrm{E}}(t+\delta t) = C_{\mathrm{E}}(t) + v(t)\delta t + \frac{1}{2}a(t)\delta t^{2}$$

The required acceleration of the reaction, a(t), was found by differentiation of eq. [5] with respect to time

$$a(t) = \frac{dv}{dt} = \{2k_{-1}^{H}[(C_{E_{0}} - C_{E}) - (k_{1}^{0} + k_{1}^{H})][H^{+}]v(t) + k_{-1}^{H}[(C_{E_{0}} - C_{E})^{2} - (k_{1}^{0} + k_{1}^{H})C_{E}]\} \times \left[\frac{-K_{a}}{\sqrt{(H_{o} + K_{a})^{2} + 4K_{a}(C_{E_{0}} - C_{E})}}\right]v(t)$$

Scheme 3.

MeOAc
$$k_1$$
 Acetic Acid + Methanol
(E) k_{-1} (A) (B)





Fig. 2. Hydrolysis of methyl acetate at 90 °C.



Results

Tables 1–3 of the Supplementary data and Fig. 1 provide the primary data for the hydrolysis of methyl acetate in water at 90°, 100° , and 110° C.

The rate constants k_1^0 , k_1^H , and k_{-1}^H were obtained by the best root-mean-square fit of the integrated C(t) to these data (Figs. 2–4).

Figures 5 and 6 are the Arrhenius plots for k_1^0 and k_1^H , and Table 4 summarizes the results. At 25 °C, the extrapolated neutral hydrolysis rate constant k_1^0 is $1.7 \pm 1.1 \times 10^{-9}$ s⁻¹.

Catalysis by HCl

Catalysis of the hydrolysis by HCl was examined to obtain an independent determination of k_1^{H} and k_{-1}^{H} . Reactions

Fig. 3. Hydrolysis of methyl acetate at 100 °C.



Fig. 4. Hydrolysis of methyl acetate at 110 °C.



Fig. 5. Arrhenius plot of k_1^0 .



Fig. 6. Arrhenius plot of k_1^H .



Table 4. Hydrolysis of methyl acetate at different temperatures.

Temperature (°C)	k_1^0 (s ⁻¹)	$k_1^{\rm H}~({\rm s}^{-1})$
110 ± 0.8	$4 \pm 1 \times 10^{-7}$	$4.2 \pm 0.3 \times 10^{-2}$
100 ± 0.8	$2.4 \pm 0.8 \times 10^{-7}$	$2.2 \pm 0.2 \times 10^{-2}$
90 ± 0.5	$1.4 \pm 0.8 \times 10^{-7}$	$1.4 \pm 0.2 \times 10^{-2}$
25	$0.17 \pm 0.11 \times 10^{-8a}$	$1.4 \pm 0.3 \times 10-4^{a}$

^aExtrapolated value.

Fig. 7. Hydrochloric acid catalysis of the hydrolysis of 1.0 mol/L ethyl acetate at 90 $^{\circ}$ C.



were performed at 90 $^{\circ}$ C using 1.0 mol/L methyl acetate and 1, 5, 7, and 9 mmol/L HCl. Tables 5–8 of the Supplementary data and Fig. 7 summarize the results.

The data of Fig. 7 were fitted to theoretical curves obtained by numerical integration of the rate equation, using the Verlet algorithm as before, with the results shown in Fig. 8. The values of $k_1^{\rm H} = 1.4 \pm 0.2 \times 10^{-2} \, {\rm s}^{-1} ({\rm mol/L})^{-1}$ and $k_{-1}^{\rm H} = 1.4 \pm 0.2 \times 10^{-3} \, {\rm s}^{-1} ({\rm mol/L})^{-2}$ are the same as in Fig. 2.

Catalysis by acetic acid

Table 9 of the Supplementary data summarizes the hydrolysis of 0.10 mol/L methyl acetate in the presence of

Fig. 8. Analysis of hydrochloric acid catalysis of the hydrolysis of 1.0 mol/L methyl acetate at 90 °C.



Fig. 9. Pseudo-first-order plot of the hydrolysis of 0.10 mol/L methyl acetate in the presence of 1.0 mol/L acetic acid.



1.00 mol/L acetic acid at 90 °C, and Fig. 9 is a pseudo-firstorder plot of the data, giving $k_{\rm obs} = 5.2 \pm 0.5 \times 10^{-5} \, {\rm s}^{-1}$.

From eq. [6] and the dissociation constant of acetic acid, the specific hydrogen-ion concentration of 1.0 mol/L acetic acid is 4.16×10^{-3} mol/L. If acetic acid functions by specific acid catalysis, i.e., $k_{obs} = k_{\rm H}[{\rm H}^+]$, $k_{\rm H}$ is calculated to be $1.3 \pm 0.1 \times 10^{-2}$ s⁻¹, identical to the value found in catalysis by HCl and in the analysis of neutral hydrolysis. It can be concluded that the hydrolysis of methyl acetate does not proceed with general acid catalysis by the product.

Supplementary data

Supplementary data for this article are available on the journal Web site (canjchem.nrc.ca) or may be purchased from the Depository of Unpublished Data, Document Delivery, CISTI, National Research Council Canada, Ottawa, ON K1A 0R6, Canada. DUD 3882. For more information on obtaining material, refer to cisti-icist.nrc-cnrc.gc.ca/cms/ unpub_e.shtml.

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