CH–CD and H_2O–D_2O Isotope Effects on the Forward and Reverse Rates of Keto–Enol Tautomerization of Acetone in Acidic Media[1]

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Abstract: The various isotope effects on the different steps of ketone enolization and enol ketonization have been isolated by kinetic measurements of the iodination and bromination of acetone and acetone-d_6, in normal and heavy water, in the presence of H_2SO_4 or $HClO_4$, and under conditions such that enolization and halogen addition to the enol occur at comparable rates. The H_2O–D_2O isotope effect (= 3,7) on the ketonization, corresponding to the ratio of the rate constants for addition of H^+ and D^+, is about the same as that observed for the hydrolysis of ethyl ether of acetone enol. This result is consistent with the Pedersen two-step mechanism for keto–enol tautomerization; the rate-determining step of ketonization is proton addition, similar to the attack of an enol ether in hydrolysis. In the transition state, the proton is half-transferred from water to substrate while the enol O–H bond is not affected. CH/CD (= 6,7) and H_2O–D_2O (= 0,54) isotope effects on the enolization rate constant are reevaluated. The variations of the ketonization and enolization rate constants in different H_2O–D_2O mixtures are also discussed.

The generally accepted[2] mechanism (mechanism I, eq 1) for acid-catalyzed enolization of a simple
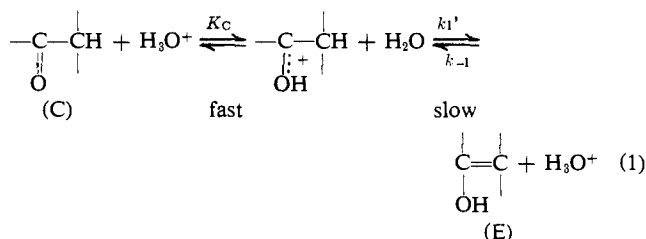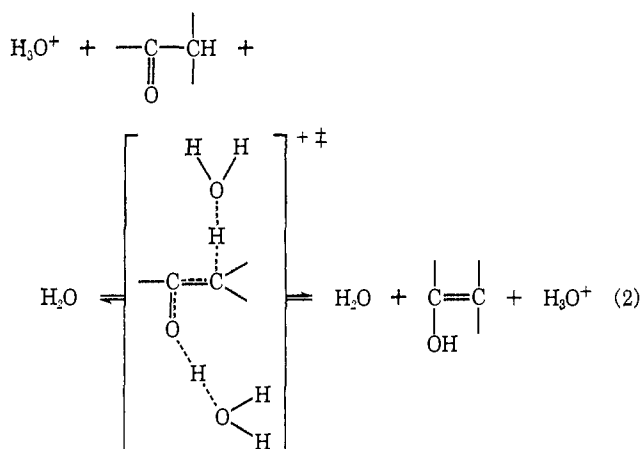

ketone, such as acetone, assumes the initial rapid formation of a hydroxycarbonium ion, the conjugate acid of acetone, followed by α-H^+ elimination under the action of a base (water in strongly acidic media) (Pedersen-type mechanism).[3]

Among the principle arguments in favor of such a mechanism, the results concerning solvent and CH–CD kinetic isotope effects have been considered particularly conclusive.[4]

The observation that there is a large CH–CD primary effect $((k_1)_H/(k_1)_D = 7.7)$[5] on the enolization rate constant (between CH_3COCH_3 and CD_3COCD_3) shows that in the rate-determining step there is α (C–H) bond breaking; a two-step mechanism cannot, however, be distinguished from a concerted mechanism (Lowry-type mechanism)[6] (mechanism II, eq 2) on this basis.

The values observed for the solvent effects on enolization rate constants $((k_1)_{H_2O}/(k_1)_{D_2O} < 1)$[5,7] have been interpreted by analogy with the A_1 and A_2 mecha-

nisms[8] (that is, with initial acid–base preequilibrium) as supporting a preequilibrium.

Such results do not, however, exclude the mechanism proposed by Palm, et al.,[9] introduced to explain the variations of the enolization rate constant at high acidities, and which proposes that the elimination of the α proton involves associated forms of the ketone and the hydroxonium ion, without there being, in the first step, complete proton transfer (mechanism III, eq 3).
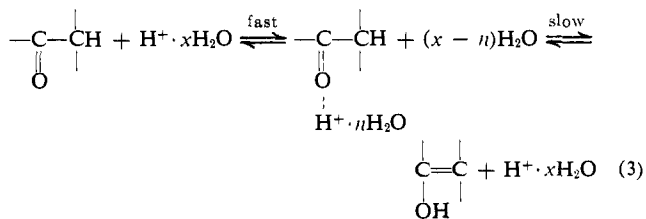
The rate-determining step is also preceded by a rapid equilibrium, and it would appear, therefore, that this

(1) (a) For a preliminary communication, see J. E. Dubois and J. Toullec, *Chem. Commun.*, 478 (1969). (b) This work is a portion of the ès-Sciences Thesis of J. Toullec, CNRS, AO 8694, Paris, 1973.

(2) See, for example, R. P. Bell, "The Proton in Chemistry," Methuen, London, 1959, p 140.

(3) K. J. Pedersen, *J. Phys. Chem.*, **38**, 581 (1934).

(4) (a) C. G. Swain, E. C. Stivers, J. F. Reuwer, and L. J. Schaad, *J. Amer. Chem. Soc.*, **80**, 5885 (1958); (b) C. G. Swain, A. J. Di Milo, and J. P. Cordner, *J. Amer. Chem. Soc.*, **80**, 5983 (1958); (c) C. G. Swain and A. S. Rosenberg, *ibid.*, **83**, 2154 (1961).

(5) O. Reitz and J. Kopp, *Z. Phys. Chem.*, *Abt. A*, **184**, 429 (1939).

(6) T. M. Lowry and I. J. Faulkner, *J. Chem. Soc.*, 2883 (1925).

(7) P. T. Mac Tigue and J. M. Sime, *Aust. J. Chem.*, **20**, 905 (1967).

(8) P. M. Laughton and R. E. Robertson, "Solute-Solvent Interactions," J. F. Coetzee and C. D. Ritchie, Ed., Marcel Dekker, New York, N. Y., 1969, p 398, and references therein.

(9) V. A. Palm, U. L. Haldna, and A. J. Talvik, "The Chemistry of the Carbonyl Group," S. Patai, Ed., Interscience, London, 1966, p 421; U. L. Haldna, H. J. Kuura, L. E. Erreline, and V. A. Palm, *Org. React.*, (*USSR*), **2**, 194 (1965); U. L. Haldna and H. J. Kuura, *ibid.*, **4**, 205 (1967).
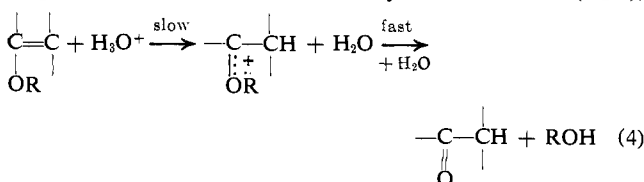
Table I. Kinetics of the Iodination of Acetone and Acetone-d_6 in L_2SO_4/L_2O Media (25 ± 0.1°)

Solvent	Substrate	$[L_2SO_4]$, N	$10^4[NaI]$, M	$10^7[I_2]_a{}^0$,[a] M	$10^5 k_I$,[b] sec^{-1}	$(k_{II}{}^{I_2})_g$,[b] M^{-1} sec^{-1}	$k_{II}{}^{I_2}$,[c] M^{-1} sec^{-1}
H_2O	CD_3COCD_3[d,e]	0.5	10	19–95	0.193	1.43	2.50
		0.2	10	9–40	0.075	1.45	2.54
		0.1	10	5–18	0.0365	1.47	2.57
D_2O[f]	CH_3COCH_3[g]	0.5	5	6–21	2.07	68.5	91.5
		0.5	10	8–30	1.97	55.0	92.0
		0.5	20	10–90	1.98	40.0	94.0
D_2O[f]	CD_3COCD_3[e,h]	0.5	8	7–30	0.307	9.3	14.3

[a] Initial analytical iodine concentration range. [b] Standard deviation, about 2%. [c] $k_{II}{}^{I_2} = (k_{II}{}^{I_2})_g(1 + K_{I_3}{}^-[I^-])$ with $K_{I_3}{}^- = 751$ in H_2O and $K_{I_3}{}^- = 676$ in D_2O.[13] [d] $[CD_3COCD_3] = 0.048$ M. [e] Deuterium content $= 99.5 \pm 0.1$ %. [f] Deuterium content $= 99.8$% min. [g] $[CH_3COCH_3] = 0.0056 - 0.016$ M. [h] $[CD_3COCD_3] = 0.020$ M.

mechanism cannot be excluded on the basis of the kinetic isotope effect on the enolization rate alone.

The peculiarity of the mechanism III relative to I lies in the fact that the formation of the O–H bond is concomitant with the breaking of the C–H bond; it is therefore a concerted mechanism. Inversely, in the ketonization of the enol, O–H rupture must be simultaneous with C–H formation. In this case, the mechanism of enol ketonization would be different from that of the hydrolysis of the corresponding ethers for which it has been clearly shown[10] that the rate-determining step is the formation of the alkoxycarbonium ion (eq 4),

$$\underset{OR}{\overset{\mid\ \ \mid}{C{=}C}} + H_3O^+ \xrightarrow{slow} \underset{\overset{\mid\ \ +\ \mid}{OR}}{\overset{\mid\ \ \ \mid}{-C-CH}} + H_2O \xrightarrow[+\,H_2O]{fast}$$

$$\underset{O}{\overset{\mid}{-C-CH}} + ROH \quad (4)$$

the analog of the hydroxycarbonium ion. Solvent isotope effects (in normal and heavy water) should then be very different for these two reactions since, for ketonization, the primary effect due to the formation of the C–H bond (or C–D bond in D_2O) would be added to the primary effect on O–H (or O–D in D_2O) rupture corresponding to the total or partial suppression of the O–L (L = H or D) stretching vibration in the transition state. *Comparison of the solvent isotope effects for enol ketonization and for the hydrolysis of the corresponding ethers constitutes therefore a very important mechanistic criterion.*

The determination of the rate constant for enol ketonization is, however, experimentally difficult on account of the very low concentration of enol for aliphatic ketones.[11] Fortunately, the ketonization isotope effects can be obtained indirectly from the kinetics of the halogenation of ketones in acidic media. In fact, we have shown recently that at very low halogen concentrations, i.e., when the ketonization and enol halogenation steps have similar rates, the following constants can be obtained.[11]

$$k_I = k_1[H^+] = k_1'K_C[H^+] \quad (5)$$

$$k_{II}{}^{X_2} = (k_1/k_{-1})k_2{}^{X_2} \quad (6)$$

(10) (a) D. M. Jones and N. F. Wood, *J. Chem. Soc.*, 5400 (1964); (b) P. Salomaa, A. Kankaanperä, and M. Lajunen, *Acta Chem. Scand.*, 20, 1790 (1966); (c) A. J. Kresge and Y. Chiang, *J. Chem. Soc. B*, 53, 58 (1967); (d) A. J. Kresge, D. S. Sagatys, and H. L. Chen, *J. Amer. Chem. Soc.*, 90, 4174 (1968); (e) D. S. Sagatys, Ph.D. Thesis, Chicago, Ill., University Microfilms, 70-10, 143 (1970); (f) A. J. Kresge, H. L. Chen, Y. Chiang, E. Murrill, M. A. Payne, and D. S. Sagatys, *J. Amer. Chem. Soc.*, 93, 413 (1971).

(11) (a) J. Toullec and J. E. Dubois, *Tetrahedron*, 29, 2851 (1973); (b) J. E. Dubois and J. Toullec, *ibid.*, 29, 2859 (1973).

k_1 = enolization rate constant (for mechanism I) (eq 1 and 5); $k_{II}{}^{X_2}$ = apparent second-order rate constant for enol halogenation, including the keto–enol equilibrium constant ($K_E = k_1/k_{-1}$) and the elementary rate constant for halogen addition to the enol, $k_2{}^{X_2}$ (eq 6).

The ratio of these two experimental constants corresponds in fact to the relative rates of addition of proton and halogen (eq 7). Thus, if the solvent isotope effect

$$k_1/k_{II}{}^{X_2} = k_{-1}/k_2{}^{X_2} \quad (7)$$

on $k_2{}^{X_2}$ (which is necessarily small relative to that on k_{-1}) is known or can be estimated, the isotope effect on the ketonization rate constant (or in other words, the ratio of the rate constants for addition of H^+ and D^+) can be determined from k_1 and $k_{II}{}^{X_2}$ measurements in D_2O and H_2O.

Apart from this isotope effect on k_{-1}, kinetic measurements in H_2O and D_2O lead to a reevaluation of the solvent isotope effect on the enolization constant for which the literature data, $(k_1)_{H_2O}/(k_1)_{D_2O} = 0.48^5$ and 0.6,[7] are somewhat inconsistent.

We considered that, in addition to the solvent isotope effect on the enol ketonization constant, it was interesting to know exactly the CH–CD isotope effect on the enolization constant.[12] These two reactions correspond to the addition of H^+ or D^+, on the one hand, to the elimination of H^+ or D^+, on the other hand; the associated primary isotope effects should therefore be complementary. For this reason, and also in order to separate the different types of effects, we have studied both CH–CD and H_2O–D_2O isotope effects. We report here the results concerning the kinetic study of the iodination and the bromination of acetone and acetone-d_6 in H_2O and D_2O.

Results

In Tables I–III are listed kinetic data for the iodination and bromination of acetone and acetone-d_6 in H_2O and D_2O, together with results for acetone bromination in H_2O–D_2O mixtures.

The rate constants k_I and $(k_{II}{}^{X_2})_g$ (apparent overall rate constant defined in terms of the analytical halogen concentrations: $[X_2]_a = [X_2] + [X_3{}^-])$[11] are deduced from studies carried out at very low bromine or iodine concentrations. Under these conditions, the ketonization of the enol and its halogen addition have comparable rates and eq 8, which makes the steady-state approxi-

(12) Reitz's results[5] for acetone $((k_1)_H/(k_1)_D = 7.7)$ are only approximate. This value is deduced from an experimental value (= 5.0) obtained by comparing the enolization of acetone with that of acetone-d_6 of isotopic purity only 92% and from an extrapolation to 100% deuterium content.

Table II. Kinetics of the Bromination of Acetone and Acetone-d_6 in L_2SO_4/L_2O Media ([NaBr] = 0.2 M; 25 ± 0.1°)

Solvent	Substrate	$[L_2SO_4]$, N	$10^7 \cdot$ $[Br_2]_a^0$,[a] M	$10^5 k_I$,[b] sec^{-1}	$(k_{II}^{Br_2})_g$,[b] M^{-1} sec^{-1}
H_2O	$CD_3COCD_3^{c,d}$	1.0	37–260	0.375	1.47
		0.5	35–175	0.182	1.57
		0.2	17–90	0.071	1.58
		0.1	7–36	0.0375	1.58
D_2O^e	$CD_3COCD_3^{d,f}$	0.5	5–26	0.320	8.65
		0.25	9–26	0.167	8.50
D_2O^e	$CH_3COCH_3^g$	0.5	11–27	2.05	55.0
D_2O/H_2O ($n = 0.80$)[h]	$CH_3COCH_3^g$	0.5	18–35	1.85	25.5
D_2O/H_2O ($n = 0.60$)[h]		0.5	10–37	1.73	17.6
D_2O/H_2O ($n = 0.40$)[h]		0.5	10–37	1.56	13.7
D_2O/H_2O ($n = 0.20$)[h]		0.5	19–65	1.42	11.5
H_2O^i	$CH_3COCH_3^g$	0.5	11–38	1.28	9.7

[a] Initial analytical bromine concentration range. [b] Standard deviation, about 2%. [c] $[CD_3COCD_3]$ = 0.048 − 0.100 M. [d] Deuterium content = 99.5 ± 0.1%. [e] Deuterium content = 99.8% min. [f] $[CD_3COCD_3]$ = 0.020 − 0.040 M. [g] $[CH_3COCH_3]$ = 0.020 − 0.030 M. [h] Isotope fraction. [i] Reference 11b.

Table III. Kinetics of the Bromination of Acetone in $LClO_4/L_2O$ ([NaBr] = 0.2 M; [$LClO_4$] = 0.5 N; 25 ± 0.1° [a]

Solvent	$10^7[Br_2]_a^0$,[b] M	$10^5 k_I$,[c] sec^{-1}	$(k_{II}^{Br_2})_g$,[c] $M^{-1} sec^{-1}$
D_2O/H_2O ($n = 0.97$)[d]	11–37	2.61	42.0
D_2O/H_2O ($n = 0.73$)[d]	14–37	2.13	20.7
D_2O/H_2O ($n = 0.49$)[d]	11–54	1.88	14.0
D_2O/H_2O ($n = 0.24$)[d]	21–70	1.59	10.6
H_2O	16–98	1.44	8.9

[a] $[CH_3COCH_3]$ = 0.014 − 0.034 M. [b] Initial analytical bromine concentration. [c] Standard deviation, about 2%. [d] Isotope fraction.

$$-\frac{d[X_2]_a}{dt} = \frac{k_1(k_2^{X_2})_g[C][X_2]_a[H^+]}{k_{-1}[H^+] + (k_2^{X_2})_g[X_2]_a} \quad (8)$$

[C], ketone concentration

mation for the enol, is valid.[11] The integrated form (eq 9) leads to the calculation of k_I and $(k_{II}^{X_2})_g$.[11]

$$\frac{t' - t}{[X_2]_a^t - [X_2]_a^{t'}} = \frac{1}{(k_{II}^{X_2})_g[C]} \times \frac{\ln [X_2]_a^t - \ln [X_2]_a^{t'}}{[X_2]_a^t - [X_2]_a^{t'}} + \frac{1}{k_I[C]} \quad (9)$$

In the case of iodination, measurements were made at different NaI concentrations, both in H_2O and D_2O. It is found, as for acetone in H_2O, that the product

$$(k_{II}^{I_2})_g(1 + K_{I_3^-}[I^-]) = k_{II}^{I_2}$$

is constant, which shows that the only iodinating agent is molecular I_2;[11a] I_3^- is excluded ($K_{I_3^-}$, formation constant of I_3^- for the equilibrium $I_2 + I^- \rightleftharpoons I_3^-$).

For bromination, on the other hand, only one concentration of NaBr (0.2 M) was used. The overall rate constants reflect bromination by Br_2 and by the complex ion Br_3^- (eq 10).[11b] The isotope effects are based on the overall rate constants. However, we shall show that the error in equating the effects on $(k_{II}^{Br_2})_g$ to those to $k_{II}^{Br_2}$ is negligible.

$$(k_{II}^{Br_2})_g = \frac{k_{II}^{Br_2} + k_{II}^{Br_3^-}/K_{Br_3^-}[Br^-]}{1 + K_{Br_3^-}[Br^-]} =$$
$$\frac{k_{II}^{Br_2}(1 + (k_2^{Br_3^-}/k_2^{Br_2})K_{Br_3^-}[Br^-])}{1 + K_{Br_3^-}[Br^-]} \quad (10)$$

$K_{Br_3^-}$, formation constant of Br_3^-

Iodination and bromination of acetone-d_6 in H_2O are accompanied by isotopic change leading to acetone-d_5 (enol ketonization by addition of a proton in competition with halogenation). In the same way, for normal acetone in D_2O, acetone-d_1 is formed. Nevertheless, during the kinetic runs, the extent of exchange is so small that isotopic purity of the ketone is hardly modified and it is possible to perform several runs on the same solution at different halogen concentrations.

Substrate Deuterium Isotope Effects. The CH–CD isotope effects are determined both for iodination and for bromination: (a) in H_2O, by comparison of the rate constants observed for acetone-d_6 (Tables I and II) with those previously observed for normal acetone under identical conditions,[11] (b) in D_2O, from the results on acetone and acetone-d_6 (Tables I and II). They are corrected to take into account the isotopic purity of acetone-d_6, 99.5 ± 0.1%, as determined by mass spectroscopy.

For bromination, $(k_{II}^{Br_2})_{g,H}/(k_{II}^{Br_2})_{g,D}$ can reasonably be equated to $(k_{II}^{Br_2})_H/(k_{II}^{Br_2})_D$; the ratio of the elementary rate constants $k_2^{Br_2}$ and $k_2^{Br_3^-}$ must in fact be identical for the enols $CD_2=C(OH)CD_3$ and $CH_2=C(OH)CH_3$.

Solvent Isotope Effects. The H_2O–D_2O isotope effects are deduced from the variations of the rate constants for iodination and bromination of acetone and acetone-d_6.

In the absence of data on the stability of the Br_3^- in D_2O, it is not possible to estimate exactly the error introduced by equating $(k_{II}^{Br_2})_{g,H_2O}/(k_{II}^{Br_2})_{g,D_2O}$ ([NaBr] = 0.2 M) with $(k_{II}^{Br_2})_{H_2O}/(k_{II}^{Br_2})_{D_2O}$. However, since the relative reactivities of Br_2 and Br_3^- are similar (in the ratio 2:1 approximately)[11] and since the effect on the equilibrium constant $K_{Br_3^-}$ must be small, and doubtlessly of the same order of magnitude as that observed for $K_{I_3^-}$,[13] the error cannot be more than 1–2%, following eq 10.

For concentrations of 0.1–1 N, H_2SO_4 is not completely dissociated into SO_4^{2-} and H^+ but is partially in the form of HSO_4^- ions. Thus, since the acidities of HSO_4^- and DSO_4^- are not identical, it is necessary to allow for the difference in the actual acidities of H_2SO_4–H_2O and D_2SO_4–D_2O of the same analytical concentrations.

Such differences in the acidities have been demonstrated by acidity functions measurements. In fact, unlike other strong acids, such as perchloric acid, the functions H_0 and D_0 are different.[14] The difference between these two functions can be used to calculate the difference in the concentrations of the H_3O^+ and D_3O^+ ions for the same acid concentration. Thus, for 0.5 N solutions, a ratio $[H_3O^+]/[D_3O^+] \approx h_0/d_0 \approx 1.12$ can be estimated. In what follows, this difference will be taken into account for the determination of the solvent

(13) R. W. Ramette and R. W. Sandford, *J. Amer. Chem. Soc.*, **87**, 5001 (1965).
(14) E. Högfeldt and J. Bigeleisen, *J. Amer. Chem. Soc.*, **82**, 15 (1960).

Table IV. CH/CD and H_2O/D_2O Isotope Effects on the Rate Constants of Acetone Iodination in L_2SO_4/L_2O Media (25°)

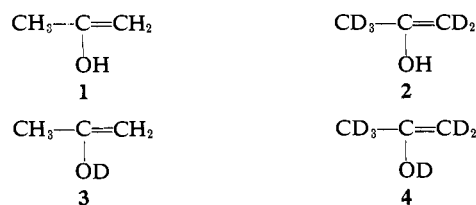|	Solvent	CH_3COCH_3	$CD_3COCD_3{}^a$	CH/CD effects
$10^5 k_1,{}^b$ M^{-1} sec^{-1}	H_2O	2.43[c]	0.373	6.5 ± 0.3[d] (6.7 ± 0.3)[e]
	D_2O	4.0	0.614	6.5 ± 0.3[d] (6.7 ± 0.3)[e]
$(k_1)_{H_2O}/(k_1)_{D_2O}$		0.61 ± 0.03[d] (0.54 ± 0.03)[f]	0.61 ± 0.03[d] (0.54 ± 0.03)[f]	
$k_{II}^{I_2}$, M^{-1} sec^{-1}	H_2O	16.5	2.54	6.5 ± 0.3[d] (6.7 ± 0.3)[e]
	D_2O	92.0	14.3	6.5 ± 0.3[d] (6.7 ± 0.3)[e]
$(k_{II}^{I_2})_{H_2O}/(k_{II}^{I_2})_{D_2O}$		0.18 ± 0.01[d]	0.18 ± 0.01[d]	
$10^6 r^g$	H_2O	1.47	1.47	1.00 ± 0.10[d]
	D_2O	0.435	0.430	1.01 ± 0.10[d]
$(r)_{H_2O}/(r)_{D_2O}$		3.4 ± 0.3[d] (3.0 ± 0.3)[f]	3.4 ± 0.3[d] (3.0 ± 0.3)[f]	

[a] Deuterium content = 99.5 ± 0.1%. [b] Enolization catalytic rate constants defined by $k_I = k_1[H^+]_a$ where $[H^+]_a$ is the analytical proton concentration expressed in equiv g/l. [c] Reference 11a. [d] Confidence limits calculated from the standard deviations on k_1 and $k_{II}^{I_2}$. [e] Extrapolated values from 99.5 to 100% deuterium content. [f] Corrected values taking into account the differences between the H_0 and D_0 acidity functions. [g] $r = k_1/k_{II}^{I_2} = k_{-1}/k_2^{I_2}$.

isotope effect on enolization and ketonization rate constants depending on the actual medium acidity.

For mixed H_2O–D_2O media, in the presence of sulfuric acid, it is necessary to take into account the dependence of the acidity on the isotopic fraction n. These variations, which are related to the dissociation constant of LSO_4^- (L = H or D), have been evaluated by assuming that this acidity constant follows the Gross–Butler equation,[15] for an overall effect $pK_{DSO_4^-} - pK_{HSO_4^-} = 0.36$.[16]

Since the enolization and the ketonization of the enol are subject to general catalysis, LSO_4^- can be involved as a catalyst. Assuming Brönsted type correlation with a slope of 0.55 as shown for the catalysis of enolization by weak acids,[17] the ratio of the H_3O^+ and HSO_4^- partial rate constants can be estimated to be 10^2. However, Rice and Urey report a ratio of $(k_1)_{H_3O^+}/(k_1)_{HSO_4^-} = 1.35$ from measurements in H_2SO_4–$KHSO_4$ solutions.[18] In fact, this ratio is more in agreement with the small difference between enolization rate constants in $HClO_4$ and H_2SO_4 media (Tables V and VI) (when $[H^+]$ is expressed in eq 5 as analytical proton concentration), than the idea that the partial rate for HSO_4^- to be negligible.

In spite of this, measurements performed in the presence of completely dissociated perchloric acid do not show differences between solvent isotope effects in sulfuric and perchloric acids. The solvent isotope effects on k_1 and on the ratio $r = k_1/k_{II}^{X_2} = k_{-1}/k_2^{X_2}$ (Table VI), obtained by extrapolation of the curves of k_1 and r against the isotope fraction n from 97 to 100%, are identical with those observed after acidity correction for bromination and iodination in L_2SO_4–L_2O (Tables IV and V). Furthermore, the k_1 and r variations vs. n are identical in L_2SO_4–L_2O and $LClO_4$–L_2O (see discussion part, Figures 3–5). It follows that, even if LSO_4^- is involved, the discussion can be developed by considering only the acid–base pair L_3O^+–L_2O.

Discussion

The different effects observed are listed in Tables IV, V, and VI. Generally speaking, the solvent isotope effects are identical for acetone and for acetone-d_6, as are the CH–CD isotope effects in normal and heavy water. The two types of effects are therefore totally independent.

CH–CD Isotope Effect on the Enolization Rate Constant. For mechanism I hypothesis, the effect on the constant k_1 corresponds to the product of a secondary isotope effect on the preequilibrium (constant K_C) and a predominant primary isotope effect on the elimination of the proton (k_1'). By analogy with the secondary isotope effects observed for the stability of carbonium ions (≈ 1.3),[19] attributed to hyperconjugation, the isotope effect on K_C must be normal ($K_H/K_D > 1$). It must, however, be markedly smaller for the hydroxycarbonium ion than for a pure carbonium ion since the charge is stabilized by resonance with the hydroxyl group.

If it is assumed that K_C is negligibly modified, the effect on k_1' must be very close to that observed on k_1. This value corresponds approximately to the theoretical maximum value ($k_H/k_D = 6.9$)[20] calculated when the proton is half-transferred from the substrate to a water molecule in the transition state (which corresponds to the total suppression of the C–H stretching vibration).

CH–CD Isotope Effects on the Apparent Rate Constants $k_{II}^{X_2}$. It is remarkable that the CH–CD isotope effect on the constant $k_{II}^{X_2}$, for bromination and for iodination, is identical with that observed for the enolization rate. This result is attributable to the fact that,

$$(k_1)_H/(k_1)_D \equiv (k_{II}^{X_2})_H/(k_{II}^{X_2})_D$$

of the different elementary rate constants k_1, k_{-1}, and $k_2^{X_2}$ in the analytical expression of $k_{II}^{X_2}$ (eq 6), only k_1 varies significantly. In passing from acetone to acetone-d_6, the effects on k_{-1} and $k_2^{X_2}$ can only be secondary effects for proton addition and halogen addition on the

(15) V. Gold, *Advan. Phys. Org. Chem.*, **7**, 259 (1969), and references therein.

(16) M. H. Lietzke and R. W. Stoughton, *J. Phys. Chem.*, **67**, 652 (1963).

(17) R. P. Bell and O. M. Lidwell, *Proc. Roy. Soc., Ser. A*, **176**, 88 (1940).

(18) F. O. Rice and H. C. Urey, *J. Amer. Chem. Soc.*, **52**, 95 (1930); R. P. Bell, "Acid-base Catalysis," Oxford University Press, London, 1941, p 91.

(19) D. S. Noyce, D. R. Hartter, and F. B. Miles, *J. Amer. Chem. Soc.*, **90**, 3794 (1968).

(20) R. P. Bell, ref 2, pp 183–214.

Table V. CH/CD and H_2O/D_2O Isotope Effects on the Rate Constants of Acetone Bromination in L_2SO_4/L_2O Media (25°)

	Solvent	CH_3COCH_3	CD_3COCD_3[a]	CH/CD effects
$10^5k_1,^b$ M^{-1} sec^{-1}	H_2O	2.50^c	0.370	6.7 ± 0.3^d
				$(7.0 \pm 0.3)^e$
	D_2O	4.1	0.630	6.5 ± 0.3^d
				$(6.7 \pm 0.3)^e$
$(k_1)_{H_2O}/(k_1)_{D_2O}$		0.61 ± 0.03^d	0.59 ± 0.03^d	
		$(0.54 \pm 0.03)^f$	$(0.53 \pm 0.03^f$	
$(k_{II}^{Br_2})_g^g$	H_2O	10.2^c	1.57	6.5 ± 0.3^d
				$(6.7 \pm 0.3)^e$
	D_2O	55.0	8.6	6.4 ± 0.3^d
				$(6.6 \pm 0.3)^e$
$(k_{II}^{Br_2})_{g,H_2O}/(k_{II}^{Br_2})_{g,D_2O}$		0.19 ± 0.1^d	0.18 ± 0.1^d	
10^6r^h	H_2O	2.46	2.36	1.03 ± 0.10^d
	D_2O	0.75	0.73	1.03 ± 0.10^d
$(r)_{H_2O}/(r)_{D_2O}$		3.3 ± 0.3^d	3.2 ± 0.3^d	
		$(2.9 \pm 0.3)^f$	$(2.9 \pm 0.3)^f$	

[a] Deuterium content = $99.5 \pm 0.1\%$. [b] Enolization catalytic rate constants defined by $k_1 = k_1[H^+]_a$ equation where $[H^+]_a$ is the analytical proton concentration expressed in equiv g/l. [c] Reference 11b. [d] Confidence limits evaluated from the standard deviations on k_1 and $k_{II}^{I_2}$. [e] Extrapolated values from 99.5 to 100% deuterium content. [f] Corrected values taking into account the differences between the H_0 and D_0 acidity functions. [g] $[NaBr] = 0.2 M$. [h] $r = k_1/(k_{II}^{Br_2})_g = k_{-1}/(k_2^{Br_2})_g$.

Table VI. H_2O/D_2O Isotope Effects on the Rate Constants of Acetone Bromination in $LClO_4/L_2O$ Media (25°)

	$10^5k_1,^a$ M^{-1} sec^{-1}	$(k_{II}^{Br_2}),^b$ M^{-1} sec^{-1}	10^6r
H_2O	2.88	8.9	3.24
D_2O	5.3^c	50^d	1.06^c
H_2O/D_2O effects	0.54 ± 0.03^e	0.18 ± 0.01^e	3.04 ± 0.03^e

[a] Enolization catalytic rate constant $(k_1 = k_1/[H^+]$ in which $[H^+]$ is the perchloric acid concentration). [b] $[NaBr] = 0.2 M$. [c] Extrapolated values from 97 to 100% deuterium content. [d] Value deduced from the extrapolated values of k_1 and r. [e] Confidence limits calculated from the standard deviations on k_1 and $k_{II}^{Br_2}$.

enols **1** and **2**, on the one hand, and on enols **3** and **4** on the other hand (depending on the solvent, H_2O or D_2O).

$$CH_3-C=CH_2$$
$$\quad\quad |$$
$$\quad\quad OH$$
$$1$$

$$CD_3-C=CD_2$$
$$\quad\quad |$$
$$\quad\quad OH$$
$$2$$

$$CH_3-C=CH_2$$
$$\quad\quad |$$
$$\quad\quad OD$$
$$3$$

$$CD_3-C=CD_2$$
$$\quad\quad |$$
$$\quad\quad OD$$
$$4$$

The identity of the isotope effects on k_1 and $k_{II}^{X_2}$ indicates that the secondary isotope effects on the ratio $k_{-1}/k_2^{X_2}$ are negligible. Furthermore, since we have recently shown that the rates of the halogenation of enols are diffusion controlled[11b] (which implies $(k_2^{X_2})_H = (k_2^{X_2})_D$), the secondary effects on the ketonization constant must be negligible (this must be related to the, probably, small stability difference between normal and α-d_6 hydroxycarbonium ions).

H_2O-D_2O Isotope Effect on the Enol Ketonization Rate Constant. The ratio r of the two experimental constants $k_1/k_{II}^{X_2}$ (eq 7), which expresses the ratio of the rate constants for the electrophilic addition of proton and halogen to the enol, is modified by the passage from normal to heavy water to the same extent (2.9–3.0) for normal and deuterioacetone, for both bromination and iodination, in sulfuric or perchloric acid.

In aqueous media, enol ketonization involves proton addition to the enols **1** and **2**, whereas in heavy water it corresponds to the addition of a deuteron to the enols **3** or **4**.

To a first approximation, it can be assumed that the secondary solvent isotope effect on the constants $k_2^{Br_2}$ and $k_2^{I_2}$ is negligible, which leads to

$$(k_{-1})_{H_2O}/(k_{-1})_{D_2O} = 3.0$$

However, since the rates of halogen addition are diffusion controlled,[11b] the H_2O-D_2O effect on halogen addition can be estimated from the difference in the viscosities of the two solvents. If we assume that the ratio of the viscosities of the aqueous acids is identical with that of normal and heavy water, and that the diffusion coefficients follow the Stokes–Einstein equation,[21] eq 11 is deduced. From these hypotheses, the

$$\frac{(k_2^{X_2})_{H_2O}}{(k_2^{X_2})_{D_2O}} = 1.23 \quad \left(= \frac{\eta_{D_2O}}{\eta_{H_2O}} \right) \quad (11)$$

ratio

$$\frac{(k_{-1})_{H_2O}}{(k_{-1})_{D_2O}} = 3.7$$

must be a better evaluation of the solvent isotope effect on enol ketonization rate constant.

Effects of the same magnitude have been observed for the hydrolysis of enol ethers,[10b-e] in which the rate-determining step is the addition of a proton to the double bond. In particular, $k_{H_3O^-}/k_{D_3O^+} = 3.5$ was observed by Kresge, Sagatys, and Chen[10d,e] for the hydroxonium ion catalyzed hydrolysis of ethyl isopropenyl ether, an ether derived from acetone enol. Furthermore, these authors showed that there was a correlation between the hydrolysis constants of a certain number of ethers and the $k_{H_3O^+}/k_{D_3O^+}$ effects. Figure 1 shows that the point for the ketonization of acetone ($k_{-1} \approx 1700 M^{-1}$ sec^{-1})[11b] falls exactly on this correlation. It can therefore be concluded that the solvent isotope effects on ether hydrolysis and enol ketonization rates are of same origin and are of the same size.

Enol ketonization is distinguished from ether hydrolysis by the presence of the O–H group (instead of O–R)

(21) From the Stokes–Einstein equation, the diffusion coefficients, which are involved in the Smoluchowski equation (see, for example E. A. Moelwyn-Hughes, "The Chemical Statics and Kinetics of Solutions," Academic Press, London, 1971, pp 98–113; D. N. Hague, "Fast Reactions," Wiley-Interscience, London, 1971, p 13) for the calculation of $k_2^{X_2}$, are inversely proportional to the viscosity.
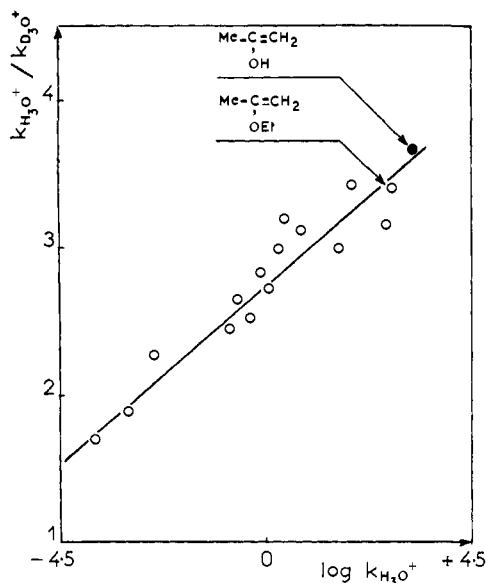
Figure 1. The ketonization of acetone enol (●) included in the Kresge–Sagatys–Chen correlation of isotope effect on reactivity for enol ethers hydrolysis (○).

Figure 2. Transition-state model for enol ether hydrolysis corresponding to half-transfer of proton ("free proton model").

the fission of which can be concomitant with proton addition on the double bond (mechanisms II and III, eq 2 and 3). From the identity of the solvent isotope effects, it can be affirmed that this cannot be the case; the O–H bond stretching vibration is scarcely affected in the transition state of the determining step. Moreover, it appears that there are no appreciable secondary effects arising either from modification of the +M effect of O–H (O–D instead O–H) on the stabilization of the hydroxycarbonium ion or from differences in solvation by H_2O and D_2O between the enol and the transition state.

This identity of the solvent isotope effects for these two reactions can be added to the already observed analogies:[11b] same order of magnitude for the ketonization and hydrolysis rates, and similar structural effects. It can thus be concluded that *the mechanisms of enol ether hydrolysis and of enol ketonization are similar*.

This conclusion recalls that of Lienhard and Wang[22] who compared indirectly the general catalysis of cyclohexanone enol ketonization with that of the hydrolysis of the corresponding ether; approximately the same value of the Brönsted α exponent is observed for the two reactions. For acetone, the same comparison can be made; the value $\alpha = 0.55$ for enol ketonization which can be deduced from the results of Bell et al.,[17] on the general catalysis of enolization by weak acids is quite close to that (0.64) measured for ethyl isopropenyl ether.[10e,f,23]

(22) G. E. Lienhard and T. C. Wang, *J. Amer. Chem. Soc.*, **91**, 1146 (1969).
(23) This finding that α has similar values for hydrolysis and ketonization of related substrates is a further argument against the $H_2O–D_2O$ effect having an origin other than the formation of the C–L bond. In fact, it could be imagined that the identity of the isotope effects for these two reactions is fortuitous, and that the effect observed for the ketonization arises merely by the superposition of two effects, one related to the rupture of O–L bond and the other to the formation of C–L bond (the latter in this case would have to be much smaller than that observed for the hydrolysis of the corresponding ether). Since the magnitude of the primary isotope effect, corresponding to the formation of the C–L bond, is a function of the extent of proton transfer in the transition state, and since the values of α are so similar, such a coincidence is scarcely plausible.
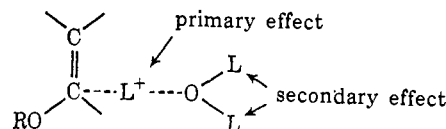
The isotope effect $k_{H_3O^+}/k_{D_3O^+} = 3.5$, observed for the hydrolysis of this ether, corresponds approximately to the maximum theoretical value (3.6) predicted by Bunton and Shiner[24] for reactions in which a proton is transferred onto an unsaturated C atom. This upper limit was calculated on the basis of a transition state model in which the proton is in electrostatic equilibrium between water and the substrate (Figure 2); the O–L bond is sufficiently broken for the stretching vibration of the O–L to be completely suppressed, while the C–L is not sufficiently formed for the C–L vibration to appear. Such a situation corresponds to the case where the proton is half-transferred in the transition state.

This maximum effect of 3.6 arises from the partial compensation of the primary effect (≈ 6), corresponding to the transfer of an atom D instead of H, by a secondary effect due to the other replacements of H by D atoms.[24]

It has been shown that such a transition-state model corresponds approximately to a Brönsted α exponent close to 0.5;[25] α is then considered to be a measure of the degree of H^+ transfer at the transition state. The value $\alpha = 0.64$ found experimentally for ethyl isopropenyl ether[10f] is in agreement with this hypothesis.

A situation closely analogous to ether hydrolysis is therefore met here for enol ketonization. The conclusions obtained for hydrolysis can be transposed to ketonization; in particular, *the proton is approximately half-transferred in the transition state*.[26]

By analogy with what has been proposed for enol ether hydrolysis[25] and for other reactions of a proton on a double bond,[8] olefin hydration,[27] for example, the overall effect observed can be broken up into *two effects, primary* and *secondary*, in accordance with the following equation.

$$\frac{(k_{-1})_{H_2O}}{(k_{-1})_{D_2O}} = \left[\frac{(k_{-1})_{H_2O}}{(k_{-1})_{D_2O}}\right]_{prim} \left[\frac{(k_{-1})_{H_2O}}{(k_{-1})_{D_2O}}\right]_{sec} \quad (12)$$

The secondary effect, which represents the effect of atoms L not involved in the transfer of L^+, is generally estimated on the assumption that it corresponds, after statistical correction (3 for H_3O^+ and 1 for HD_2O^+), to the ratio of the rates of addition of H^+ from ions H_3O^+ and HD_2O^+ (eq 13). The constants $(k_{-1})_{H_3O^+}$ and

$$\left[\frac{(k_{-1})_{H_2O}}{(k_{-1})_{D_2O}}\right]_{sec} = \frac{(k_{-1})_{H_3O^+}}{3(k_{-1})_{HD_2O^+}} \quad (13)$$
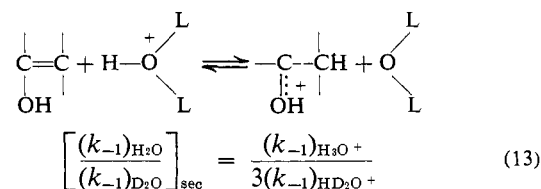
(24) C. A. Bunton and V. G. Shiner, *J. Amer. Chem. Soc.*, **83**, 3207 (1961).
(25) M. M. Kreevoy and R. Eliason, *J. Phys. Chem.*, **72**, 1313 (1968).
(26) An identical conclusion, based on less experimental data (isotope effects on the enolization rate constants), has been proposed by Swain and Rosenberg.[4c]
(27) V. Gold, *Trans. Faraday Soc.*, **56**, 255 (1960).

Toullec, Dubois / Keto–Enol Tautomerization of Acetone in Acidic Media

$(k_{-1})_{HD_2O^+}$ must be related by a Brönsted correlation to the acidity constants $K_{HD_2O^+}$ and $K_{H_3O^+}$ corresponding to the release of H^+. These acidity constants are defined from the equilibria

$$HL_2O^+ + H_2O \rightleftharpoons L_2O + H_3O^+$$
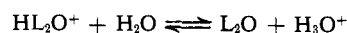
The theory of solutions in H_2O–D_2O mixtures predicts[15]

$$K_{HD_2O^+} = 1/3l^2 \qquad (14)$$

where l is the fractionation factor for D atoms between lyonium ions and the solvent.[15] l is an experimental

$$l = (D/H)_{L_3O^+}/(D/H)_{L_2O}$$

value generally taken to be 0.69.[15] Thus, since $K_{H_3O^+} = 1$, the secondary effect can be evaluated from[28]

$$\left[\frac{(k_{-1})_{H_2O}}{(k_{-1})_{D_2O}}\right]_{sec} = \left[\frac{K_{H_3O^+}}{3K_{HD_2O^+}}\right]^\alpha = l^{2\alpha}$$

For the ketonization of acetone enol, the secondary isotope effect is therefore equal to 0.69 if α is taken to be 0.5.

The primary effect corresponds to the breaking of a O–H or O–D bond and expresses, after statistical correction, the ratio of the rates of transfer of $L=\!\!H$ and $L=\!\!D$ from the ions LH_2O^+. It can be calculated,
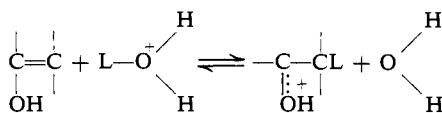
from eq 12, from the overall effect and the secondary effect. Thus a value of 3.7 corresponds to a primary effect of 5.4. This value is close to the theoretical maximum.

CH–CD and H_2O–D_2O Isotope Effects on the Keto–Enol Equilibrium Constant. For normal acetone in heavy water, k_1/k_{-1} expresses the ratio of the rate constants for C–H bond rupture and C–D bond formation; it does not therefore correspond to a true equilibrium constant. The solvent isotope effect is therefore the ratio of the individual effects on k_1 and k_{-1}. In the same way for acetone-d_6 in normal water, the forward reaction is C–D bond breaking and the back reaction is C–H bond formation.

For acetone-d_6 in heavy water, on the other hand, K_E is a true equilibrium constant, and the k_{II} values observed under these conditions for bromination and iodination can be used for the comparison with K_E for normal acetone in water. From eq 6

$$\frac{(K_E)_{H,H_2O}}{(K_E)_{D,D_2O}} = \frac{(k_{II}^{X_2})_{H,H_2O}}{(k_{II}^{X_2})_{D,D_2O}} \frac{(k_2^{X_2})_{D,D_2O}}{(k_2^{X_2})_{H,H_2O}}$$

If it is accepted as previously that the ratio of the addition rate constants corresponds to that of the viscosities ($(k_2^{X_2})_{H_2O}/(k_2^{X_2})_{D_2O} = 1.23$), $(K_E)_{H,H_2O}/(K_E)_{D,D_2O}$ takes a value very close to 1.[29] Such an identity of these constants is particularly remarkable.

(28) The Brönsted equation is expressed in the form

$$k_{HA}/p = G_A[qK_{HA}/p]^\alpha$$

where p is the number of acid proton of HA, q is the number of basic sites of the conjugated base, and G_A is a constant. Since H_3O^+ and HD_2O^+ can release 3 and 1 protons, respectively, the catalytic constants for H_3O^+ and HD_2O^+ are $(k_{-1})_{H_3O^+}/3 = G_A[K_{H_3O^+}/3]^\alpha$ and $k_{HD_2O^+} = G_A(K_{HD_2O^+})^\alpha$.

(29) From the experimental values of $k_{II}^{X_2}$ (Tables IV and V) and taking into account the correction for the isotopic purity of acetone-d_6.

H_2O–D_2O Isotope Effect on Enolization Rate Constant. If mechanism I is assumed, the variations in the enolization rate constant arise (eq 15) from the

$$\frac{(k_1)_{H_2O}}{(k_1)_{D_2O}} = \frac{(K_C)_{H_2O}}{(K_C)_{D_2O}} \frac{(k_1')_{H_2O}}{(k_1')_{D_2O}} \qquad (15)$$

effects on the acid–base preequilibrium constant K_C and on the elimination constant k_1'. $(K_C)_{H_2O}/(K_C)_{D_2O}$ corresponds to the reciprocal of the ratio of the acidity constants of the ions $CL_3C(OH)CL_3^+$ and $CL_3C(OD)$-CL_3^+ in H_2O and D_2O (acidity in the sense of H^+ or D^+ release). As for the ratio $(k_1')_{H_2O}/(k_1')_{D_2O}$, it results from the difference of the basicity of H_2O and D_2O which are involved in the elimination either of a proton (in the case of CH_3COCH_3) or of a deuteron (CD_3-$COCD_3$).

For normal acetone, the two rate constants $(k_1')_{H_2O}$ and $(k_1')_{D_2O}$ must be related (eq 16, taking into account

$$\frac{(k_1')_{H_2O}}{(k_1')_{D_2O}} = \left[\frac{3K_{HD_2O^+}}{K_{H_3O^+}}\right]^{1-\alpha} = l^{-2(1-\alpha)} \qquad (16)$$

eq 13 and 14) by another Brönsted equation to the acidity constants of the conjugate acids of H_2O and D_2O.[30] For $\alpha = 0.5$, this effect on k_1' must be equal to 1.45 (1/0.69).

For acetone-d_6, an identical expression for the elimination of D^+, under the influence of H_2O and D_2O, is obtained in the same way. This shows that the secondary solvent isotope effect on the rate of elimination of H^+ or of D^+ does not depend on the entity eliminated. The observation that the H_2O–D_2O effects on the enolization constant do not depend on the substrate is in agreement with theory.

The H_2O–D_2O effect on the preequilibrium constant K_C can then be deduced from the experimental value, in accordance with eq 15. It is interesting to note that

$$(K_C)_{H_2O}/(K_C)_{D_2O} = 0.37 \ (0.54/1.45)$$

this effect corresponds approximately to those observed for some A_1 mechanism reactions, involving in particular oxygen-containing substrates as for acetone (acetal hydrolysis, for example). For reactions of this type, the initial preequilibrium step is followed by a slow unimolecular step. In this case, therefore, only the solvent isotope effect on the initial preequilibrium constant is involved.

Enolization Rate Constants in H_2O–D_2O Mixed Media. As in the preceding discussion, it is necessary to distinguish the effects on the acid–base constant K_C and on the elimination constant k_1'.

By means of the classical Gross–Butler equation, recently discussed by Gold[15] and by Laughton and Robertson,[8] the acidity constant of an acid LA in a H_2O–D_2O mixture, of isotope fraction n, can be calculated when the overall effect K_{HA}/K_{DA} is known. The constant K_C, which is the reciprocal of the acidity constant of the hydroxycarbonium ion, the conjugated acid of the ketone, must follow the same law.

$$\frac{(K_C)_n}{(K_C)_{H_2O}} = \frac{1 - n + nl^3(K_C)_{D_2O}/(K_C)_{H_2O}}{(1 - n + nl)^3} \qquad (17)$$

(30) For base catalysis, the Brönsted equation is $k_B/q = G_B p \cdot (1/K_{BH^+})/q]^\beta$, where p is the number of acid protons in BH^-, q is the number of basic sites in B, and G_B is a constant. For the elimination of H^+ by H_2O and D_2O: $(k_1')_{H_2O} = G_B(3/K_{H_3O^+})^\beta$ and $(k_1')_{D_2O} = G_B(1/K_{HD_2O^+})^\beta$, whence $(k_1')_{H_2O}/(k_1')_{D_2O} = [3K_{HD_2O^+}/K_{H_3O^+}]^\beta$, where $\beta = 1 - \alpha$ since $\alpha + \beta = 1$ for the forward and inverse processes.
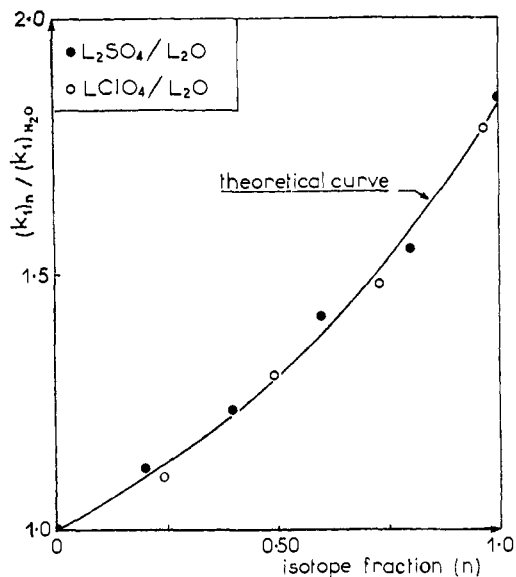
Figure 3. Experimental and calculated dependence of the enolization rate constant k_1 of acetone on the isotope fraction n of H_2O–D_2O mixtures.

For the slow step, the elimination, it can be considered that the three species react as bases with their own constants so that

$$\frac{(k_1')_n}{(k_1')_{H_2O}} = \frac{[H_2O]}{[L_2O]} + \frac{(k_1')_{HDO}[HDO]}{(k_1')_{H_2O}[L_2O]} +$$

$$\frac{(k_1')_{D_2O}}{(k_1')_{H_2O}}\frac{D_2O}{L_2O} \quad (18)$$

$$[L_2O] = [H_2O] + [HDO] + [D_2O]$$

From the theory of H_2O–D_2O mixtures, the concentrations ratio of the three species, H_2O, D_2O, and HDO, can be estimated in terms of n. The different constants

$$[H_2O]/[L_2O] = (1 - n)^2$$

$$[HDO]/[L_2O] = 2n(1 - n) \quad (19)$$

$$[D_2O]/[L_2O] = n^2$$

$(k_1')_{L_2O}$ are related to the acidity constants of the conjugated acids by a Brönsted-type equation, with exponent $1 - \alpha$, taking account of the different statistical terms[31]

$$\frac{(k_1')_{H_2O}}{(k_1')_{HDO}} = \left[\frac{3K_{H_2DO^+}}{2K_{H_3O^+}}\right]^{1-\alpha} = l^{\alpha-1} \quad (20)$$

and $(k_1')_{H_2O}/(k_1')_{D_2O}$ given in eq 16. The combination of eq 16 and 18–20 leads to eq 21 for which the dependence of k_1 on n can be calculated.

$$(k_1')_n/(k_1')_{H_2O} = (1 - n + nl^{1-\alpha})^2 \quad (21)$$

For each H_2O–D_2O mixture, we have calculated the ratio $(k_1)_n/(k_1)_{H_2O}$ from eq 17 and 21, given in eq 5. Figure 3 shows that the experimental results coincide with the theoretical curve for $\alpha = 0.5$. Such agreement does not, however, constitute proof that $\alpha = 0.5$.[32] In fact, the theoretical curves calculated in this way for the different values of α are only slightly separated.

(31) $K_{H_2DO^+} = (2/3l)K_{H_3O^+}$.[15]

(32) The dependence of the acidity of L_2SO_4/L_2O mixtures on n is allowed for (see results part).

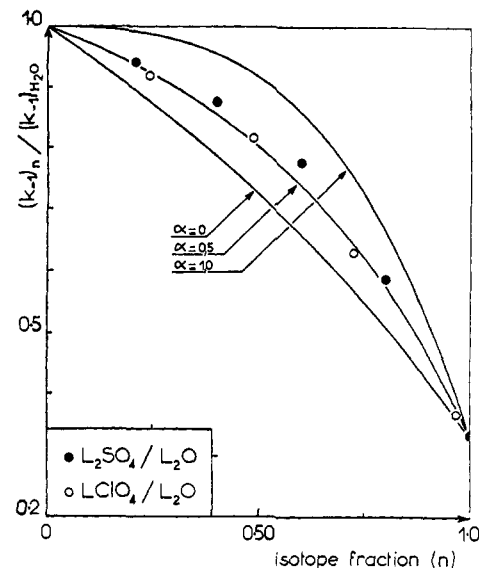**Figure 4.** Dependence of the rate constant for ketonization (k_{-1}) of acetone enol on the isotope fraction n for H_2O–D_2O mixtures, calculated for $(k_2^{Br_2})_g$ = constant (hypothesis a). Comparison with the calculated curves corresponding to eq 22 for different values of α.
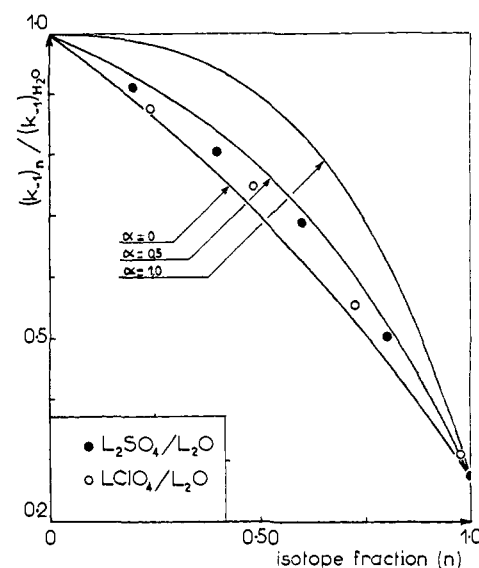

Figure 5. Dependence of the rate constant for ketonization (k_{-1}) of acetone enol on the isotope fraction n for H_2O–D_2O mixtures, calculated for $(k_2^{Br_2})_g \propto 1/\eta$ (hypothesis b).[32] Comparison with the calculated curves corresponding to eq 22 for different value of α.

Enol Ketonization Rate Constants in H_2O–D_2O Mixed Media. The theoretical study of the effect of n on the rates of proton addition to an unsaturated C atom has been developed by Gold,[11,33] Kresge,[34] and Salomaa.[10b] The results of this approach have been compared with experimental data for olefin hydration[33,35] and for enol ether hydrolysis,[10b,c] for example. From the theoretical relationship, can be calculated the rate constant for addition of L^+ in a medium of isotopic fraction n (eq 22), when the overall effect k_{H_2O}/k_{D_2O} and the

(33) V. Gold and M. A. Kessick, *J. Chem. Soc.*, 6718 (1965).

(34) A. J. Kresge, *Pure Appl. Chem.*, **8**, 243 (1964).

(35) J. C. Simandoux, B. Torck, M. Hellin, and F. Coussemant, *Tetrahedron Lett.*, 2971 (1967); *Bull. Soc. Chim. Fr.*, 4410 (1972).

$$\frac{k_n}{k_{H_2O}} = \frac{(1 - n + nl^{1-\alpha})^2(1 - n + nl^{1+2\alpha}k_{D_2O}/k_{H_2O})}{(1 - n + nl)^3} \quad (22)$$

α parameter, corresponding to the exponent α of the Brönsted correlations, are known.

For enol ketonization eq 22 must also be obeyed. In Figures 4 and 5, $(k_{-1})_n/(k_{-1})_{H_2O}$ for different H_2O–D_2O mixtures is compared with the curves calculated for different arbitrary values of α. The values of $(k_{-1})_n/(k_{-1})_{H_2O}$ have been determined from the variations of $(k_{-1}/(k_2^{Br_2})_g)_n/(k_{-1}/(k_2^{Br_2})_g)_{H_2O}$ with two different assumptions: (a) the constant $(k_2^{Br_2})_g$ is independent of n (Figure 4)[32] and (b) the bromination constant varies linearly with the fluidity $(1/\eta)^{36}$ of the H_2O–D_2O mixtures (Figure 5).[32] Depending on which of these hypotheses is taken, the experimental points are either above or below the curve calculated for $\alpha = 0.5$, showing that the isotope effect on the enol bromination rate is probably overestimated by hypothesis (b). However, in

(36) The viscosities of a mixture of two solvents A and B are generally calculated from Bingham's law $(1/\eta = x_A/\eta_A + x_B/\eta_B)$ where η_A, η_B, x_A, and x_B are the viscosities and the molar fraction of A and B. This law has been found to be approximately valid for H_2O–D_2O mixtures: G. Jones and H. L. Fornwalt, *J. Chem. Phys.*, 4, 30 (1936).

view of the experimental errors, no more definite conclusion can be drawn. The value of $\alpha = 0.5$ is consistent with the observed variations in r. These results confirm the parallelism of the mechanisms of enol ketonization and the hydrolysis of the corresponding ethers.

Experimental Section

Electroorganic Chemistry. XII.[1] Anodic Oxidation of Enol Esters

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Abstract: Electrochemical oxidation of a number of enol esters was carried out at a carbon rod anode in acetic acid. The products consisted of four types of compounds: conjugated enones, α-acetoxy carbonyl compounds, *gem*-diacetoxy compounds, and triacetoxy compounds. The product distribution was influenced by the structure of the starting compound. The oxidation of the enol ester prepared from α-alkylcycloalkanone gave the conjugated enone exclusively. The product structure, the current–potential relationship, and the polarographic oxidation potential suggest a mechanism involving an initial electron transfer from the enol ester to the anode followed by proton ejection or nucleophilic attack of the solvent.
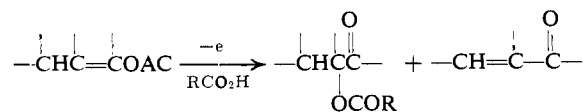
In our continuing study on the anodic oxidation of a series of aliphatic compounds, the main research interest focussed on the formation and reaction of the unstable electron-deficient intermediates which are difficult to generate in solution by the usual chemical methods.

It has been clarified that the anodic oxidation of an olefin is initiated by an electron transfer from the unsaturated bond to the anode and that the lowering of the oxidation potential of the unsaturated system is a favorable factor in the anodic oxidation.[2]

Thus, an enol ester, easily obtainable from the corresponding ketone, is expected to show the oxidation potential which is accessible by the anodic oxidation technique, and the active intermediate anodically gen-

(1) Paper XI: T. Shono and M. Mitani, *Tetrahedron*, 28, 4747 (1972).
(2) (a) T. Shono and A. Ikeda, *J. Amer. Chem. Soc.*, 94, 7892 (1972); (b) V. D. Parker and L. Eberson, *Chem. Commun.*, 340 (1969).

erated from an enol ester should show quite interesting chemical behavior.[3]

Indeed, the anodic oxidation of enol esters gave a novel and remarkable synthesis of α-acyloxy or α,β-unsaturated carbonyl compounds.

$$-\underset{|}{\overset{|}{C}}HC=\underset{|}{\overset{|}{C}}OAC \xrightarrow[RCO_2H]{-e} -\underset{|}{\overset{|}{C}}H\overset{O}{\underset{|}{\overset{||}{C}C}}- + -CH=\overset{O}{\overset{||}{C}}-\overset{O}{\overset{||}{C}}-$$
$$\underset{OCOR}{\quad}$$

Results

Preparative Oxidation of Enol Acetates. The preparative oxidation of enol acetates (1–14) was carried out at room temperature in acetic acid containing

(3) Typical reactions of enol esters: H. C. Brown and R. L. Sharp, *J. Amer. Chem. Soc.*, 90, 2915 (1968); A. Suzuki, K. Ohmori, and M. Itoh, *Tetrahedron*, 25, 3707 (1969); D. Bellus and P. Hrdlovic, *Chem. Rev.*, 67, 599 (1967); R. J. P. Allan, J. McGee, and P. D. Ritchie, *J. Chem. Soc.*, 4700 (1957); R. F. Heck, *J. Amer. Chem. Soc.*, 90, 5535 (1968).