Table II. Results of Finite Perturbation–INDO Calculations on Ethyl, Isopropyl, and *tert*-Butyl Compounds, $C_B–C_A–X^a$

	Ethyl[b]				Isopropyl				*tert*-Butyl			
X	$J_{CC}{}^b$	$P_{s_{CA}s_{CB}}{}^2$	$P_A{}^c$	P_B	J_{CC}	$P_{s_{CB}s_{CA}}{}^2$	P_A	P_B	J_{CC}	$P_{s_{CA}s_{CB}}{}^2$	P_A	P_B
CO_2H	39.3	0.0596	4.0186	3.9272	40.6	0.0574	4.0181	3.9315	39.2	0.0545	4.0138	3.9294
$COCH_3$	40.0[d]	0.0593	4.0066	3.9338	39.8	0.0570	3.9935	3.9292	40.5	0.0549	3.9996	3.9308
CN	40.7	0.0588	3.9397	3.9378	40.7	0.0566	3.9336	3.9382	39.9	0.0539	3.9353	3.9374
									(41.1)[e]	(0.0548)		
H	41.5	0.0620	3.9457	3.9457	42.1	0.0602	3.9391	3.9453	42.0	0.0578	3.9398	3.9439
									(43.3)	(0.0589)		
C_6H_5	41.6	0.0599	3.9410	3.9417	44.1	0.0586	3.9422	3.9458	42.0	0.0553	3.9513	3.9404
NO_2	41.9	0.0624	3.9430	2.9488	44.1	0.0610	3.9368	3.9525	43.0	0.0582	3.9325	3.9503
CH_3	42.1	0.0602	3.9391	3.9453	42.0	0.0578	3.9398	3.9439	41.0	0.0550	3.9461	3.9418
NH_2	47.0	0.0644	3.8223	3.9682	47.2	0.0620	3.8270	3.9657	45.5	0.0586	3.8432	3.9652
OCH_3	47.6[d]	0.0660	3.7478	3.9857	50.8	0.0643	3.7657	3.9860	48.9	0.0610	3.7771	3.9809
									(50.3)	(0.0620)		
OH	49.6	0.0672	3.7495	3.9798	48.7	0.0638	3.7668	3.9858	47.6	0.0608	3.7764	3.9777
F	49.6	0.0679	3.6787	4.0000	50.1	0.0655	3.6890	3.9968	48.7	0.0622	3.7053	3.9933

[a] J_{CC} values in Hz. [b] Taken from ref 2 unless otherwise noted. [c] Valence-shell atomic electron density of carbon A, *i.e.*, $P_{2s2s} + P_{2p_x2p_x} + P_{2p_y2p_y} + P_{2p_z2p_z} = P$. [d] Determined in this study. [e] Values in parentheses correspond to calculations in which the $C_B–C_A–C_B$ angle is 115°.

carried out for selected substituents using CCC angles larger (by 5.5°) than the tetrahedral value. The resulting shifts in J_{CC}, shown in Table II, are of the appropriate sense so as to bring the computed results into more general qualitative agreement with experiment. It was found that the majority of the increase in computed J_{CC} upon expanding the CCC angle is accounted for, as expected, by altered carbon hybridization, as manifested by changes in $P_{s_{CA}s_{CB}}{}^2$, the square of the bond order between the 2s orbitals of the coupled carbons.[22]

The experimental data and computed results of this study are consistent with the following view of substituent effects on $^{13}C–^{13}C$ coupling constants in the ethyl, isopropyl, and *tert*-butyl series. Within a given series, an electron-withdrawing substituent may be considered qualitatively to enhance the s character of the C–C bond and thus to increase the Fermi contact coupling. For a given substituent, substitution of methyl groups for hydrogens at the α carbon tends to increase the s character in the C–C bond by sterically inducing minor changes in bond angles and hence in hybridization. Thus the coupling constant goes up with the number of methyl groups attached to the α carbon. Studies of $^{13}C–^{13}C$ coupling constants in *n*-propyl, isobutyl, and neopentyl compounds would be useful in testing this interpretation. Experiments to this end are under way. It can be noted that preliminary data on *n*-propyl compounds support the interpretation based upon steric effects.

Acknowledgment. The authors are grateful to the National Science Foundation, which provided funds toward the purchase of the spectrometer and data system. They also acknowledge helpful discussions with Richard L. Elliott.

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[22] G. E. Maciel, J. W. McIver, Jr., N. S. Ostlund, and J. A. Pople, *J. Amer. Chem. Soc.*, **92**, 11 (1970).

Anomalous Kinetic Hydrogen Isotope Effects on the Rate of Ionization of Some Dialkyl Substituted Ketones

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Abstract: The rates of hydroxide catalyzed H^+, D^+, and T^+ transfer from 2,4-dimethyl-3-pentanone and 3,5-dimethyl-4-heptanone have been measured over a temperature range. The Arrhenius plots are linear and the deuterium isotope effects are normal. These results suggest that tunneling is not significant in these reactions. The rates of H^+ and T^+ transfers are similar and apparently there is no tritium isotope effect. The results suggest that in detritiation, T^+ transfer is not the rate determining step. A mechanism for tritium–hydrogen exchange has been proposed.

It was reported[1] that the Arrhenius plot for the bromination of 2,4-dimethyl-3-pentanone catalyzed by hydroxide ion exhibited pronounced curvature at temperatures below 20°. This deviation was ascribed to tunneling of the proton through the energy barrier.[1] The Arrhenius plot for the hydroxide ion catalyzed detritiation[2] of 2,4-dimethyl-3-pentanone showed a sharp break at approximately 40°. This was attributed to a

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[1] J. R. Hullet, *J. Chem. Soc.*, 430 (1965).

[2] J. R. Jones, *Trans. Faraday Soc.*, **61**, 2456 (1965).

Table I. Ionization Rate Coefficients (l. mol^{-1} sec^{-1})[a]

Compound	Temp, °C	$10^4k^{H}{}_{OH^-}$	$10^4k^{D}{}_{OH^-}$	$10^4k^{T}{}_{OH^-}$
2,4-Dimethyl-3-pentanone	0.2	2.4 ± 0.02	0.372 ± 0.005	1.14 ± 0.01
	20.0	12.2 ± 0.05	1.950 ± 0.008	6.03 ± 0.03
	25.0	17.8 ± 0.02	2.920 ± 0.02	8.90 ± 0.05
	30.0	24.6 ± 0.13	4.420 ± 0.03	12.90 ± 0.05
	35.0	36.3 ± 0.18	6.610 ± 0.03	18.20 ± 0.08
	40.0	51.2 ± 0.25	9.340 ± 0.04	26.10 ± 0.14
3,5-Dimethyl-4-heptanone	0.2	0.205 ± 0.002	0.0537 ± 0.0003	0.110 ± 0.001
	20.0	1.210 ± 0.002	0.3360 ± 0.0028	0.660 ± 0.001
	25.0	1.850 ± 0.007	0.5030 ± 0.0030	0.998 ± 0.003
	30.0	2.720 ± 0.015	0.7780 ± 0.005	1.450 ± 0.010
	35.0	4.066 ± 0.025	1.170 ± 0.008	2.140 ± 0.020
	40.0			3.230 ± 0.020

[a] Obtained from base-catalyzed bromination.

dynamic steric effect. The above results of bromination in conjunction with detritiation disclose the following features: (a) $k^{H}{}_{OH^-}/2k^{T}{}_{OH^-} = 0.98$ at 30° and remains the same in the temperature range 0–40°, (b) $A_H/2A_T = 0.43$, (c) very small difference between the activation energies ($E_T - E_H = 500$ cal mol^{-1}). None of these features are indicative[3] of tunneling. Thus, the situation regarding 2,4-dimethyl-3-pentanone is not clear and further investigation is required to explain the results more satisfactorily.

The current work was undertaken to determine whether or not a nonlinear Arrhenius plot would be obtained for the hydroxide ion catalyzed bromination of 2,4-dideuterio-2,4-dimethyl-3-pentanone. Further, it was considered interesting to investigate the rates of H^+, D^+, and T^+ transfers from substrates similar to 2,4-dimethyl-3-pentanone but in which the ionizable proton is surrounded by larger nonionizable groups. 3,5-Dimethyl-4-heptanone was chosen for this purpose. Since our method of measuring the rate of bromination of 2,4-dideuterio-2,4-dimethyl-3-pentanone differed from that adopted by Hullet[1] for 2,4-dimethyl-3-pentanone, the bromination rates of 2,4-dimethyl-3-pentanone were measured by our method to ensure that comparison of H^+ and D^+ transfer would have significance. In the current work, significant deuterium isotope effects were observed for 2,4-dimethyl-3-pentanone whereas in the previous study[2] no tritium isotope effects were observed. Hence it was considered necessary to measure the rates of T^+ transfer to confirm the absence of tritium isotope effects.

Results

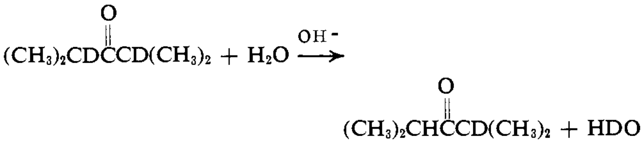
2,4-Dimethyl-3-pentanone and 3,5-dimethyl-4-heptanone react with alkaline solutions of bromine according to the general equation

$$R_1R_2CHCOCHR_1R_2 + OBr^- \longrightarrow R_1R_2CHCOC(Br)R_1R_2 + OH^- \quad (1)$$

Cullis and Hashmi[4] reported that in the bromination of 2,4-dimethyl-3-pentanone, 2 mol of OBr^- are consumed by 1 mol of ketone. Monobromoisobutyric acid and 2-propanol were found to be the products. The second step of the bromination appeared to be

$$(CH_3)_2CHCOCBr(CH_3)_2 + OBr^- \xrightarrow{OH^-} (CH_3)_2CBrCOO^- + (CH_3)_2CHOH + Br^- \quad (2)$$

Our work established the uptake of 1 mol of OBr^- by 1 mol of ketone. It seems that under the current experimental conditions only simple monobromination is important and the second step is very slow. This has been confirmed by comparing the rate of bromination and the rate of the first deuterium–hydrogen exchange reaction.



$$(CH_3)_2CD\overset{\overset{\displaystyle O}{\|}}{C}CD(CH_3)_2 + H_2O \xrightarrow{OH^-} (CH_3)_2CH\overset{\overset{\displaystyle O}{\|}}{C}CD(CH_3)_2 + HDO$$

The two rates are similar and confirm the above assumption.

Table I contains the ionization coefficients $k^{H}{}_{OH^-}$, $k^{D}{}_{OH^-}$ (both obtained from bromination), and $k^{T}{}_{OH^-}$. Table II contains the ionization rate coefficient $k^{D}{}_{OH^-}$ (obtained from the exchange reaction). Table III contains the Arrhenius parameters calculated by the method of least squares. Tables IV and V contain the deuterium and tritium isotope effects, respectively. In order to obtain the tritium isotope effects, it is necessary[5] to introduce a statistical factor of 2 since in the substrates there are two ionizable protons but only one ionizable triton per molecule.

Table II. Ionization Rate Coefficient $k^{D}{}_{OH^-}$ (l. mol^{-1} sec^{-1})[a]

Compound	Temp, °C	$10^4k^{D}{}_{OH^-}$
2,4-Dimethyl-3-pentanone	25.0	2.74 ± 0.024

[a] Obtained from base-catalyzed deuterium–hydrogen exchange.

Table III. Arrhenius Parameters for H^+, D^+, and T^+ Transfers[a]

Compound	2,4-Dimethyl-3-pentanone	3,5-Dimethyl-4-heptanone
E_H	13.04 ± 0.03	14.35 ± 0.32
E_D	13.82 ± 0.01	14.72 ± 0.23
E_T	13.36 ± 0.19	14.35 ± 0.16
A_H	(6.38 ± 0.02)10^6	(6.03 ± 0.06)10^6
A_D	(4.06 ± 0.04)10^6	(6.3 ± 0.03)10^6
A_T	(5.54 ± 0.04)10^6	(3.31 ± 0.02)10^6

[a] E in kcal mol^{-1} and A in l. mol^{-1} sec^{-1}.

Experimental Section

Materials. 2,4-Dimethyl-3-pentanone and 3,5-dimethyl-4-heptanone were purchased from Aldrich Chemical Co., Milwaukee,

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[3] R. P. Bell, "Proton in Chemistry," Cornell University Press, New York, N. Y., 1959, p 211.

[4] (a) C. F. Cullis and M. H. Hashmi, *J. Chem. Soc.*, 3080 (1957); (b) *ibid.*, 1548 (1957).

[5] D. M. Bishop and K. J. Laidler, *J. Chem. Phys.*, **42**, 1688 (1965).

Table IV. Deuterium Isotope Effects

Compound	Temperature, °C	$k^{H}_{OH^-}/k^{D}_{OH^-}$	$E_D - E_H$, kcal mol^{-1}	A_D/A_H
2,4-Dimethyl-3-pentanone	0.2	6.45		
	20.0	6.25		
	25.0	6.09	0.78	0.636
	30.0	5.56		
	35.0	5.49		
	40.0	5.48		
3,5-Dimethyl-4-heptanone	0.2	3.81		
	20.0	3.61		
	25.0	3.67	0.37	0.874
	30.0	3.49		
	35.0	3.47		

Table V. Tritium Isotope Effects

Compound	Temp, °C	$k^{H}_{OH^-}/2k^{T}_{OH^-}$	$E_T - E_H$	$2A_T/A_H$
2,4-Dimethyl-3-pentanone	0.2	1.05		
	20.0	1.01	0.32	1.736
	25.0	1.00		
	30.0	0.95		
	35.0	0.99		
	40.0	0.98		
3,5-Dimethyl-4-heptanone	0.2	0.938		
	20.0	0.916	0	1.09
	25.0	0.920		
	30.0	0.937		
	35.0	0.957		

Wis., and their purity was established by gas chromatography. Tritiated water and PPO were obtained from New England Nuclear, Boston, Mass. D_2O was purchased from Stoler Isotope Chemicals, Rutherford, N. J. Toluene (scintanalyzed) was obtained from Fisher Chemical Co., King of Prussia, Pa.

Reagent-grade bromine and distilled water, boiled to remove carbon dioxide, were used on all occasions. Carbonate-free sodium hydroxide was prepared in the customary manner.

Preparation of Deuterated Compounds. (a) **2,4-Dideuterio-2,4-dimethyl-3-pentanone.** One gram of 2,4-dimethyl-3-pentanone was placed in a glass stoppered flask with 20 ml of 1 *M* NaOD solution. After stirring for 48 hr, the ketone was separated and added to 20 ml of fresh 1 *M* NaOD solution and stirred for 24 hr. The ketone was separated and washed with 1 ml of D_2O. Both nmr analysis and mass spectral analysis showed greater than 99% deuteration had occurred in the 2 and 4 positions.

(b) **3,5-Dideuterio-3,5-dimethyl-4-heptanone.** One gram of 3,5-dimethyl-4-heptanone was placed in a glass stoppered flask with 3 ml of a 5.0 *M* solution of sodium ethoxide in D_2O. The solution was stirred magnetically for 48 hr. Five milliliters of D_2O was added to separate the ketone from the aqueous layer. The process was repeated with fresh ethoxide solution and the solution stirred for 24 hr. The nmr analysis of the separated ketone showed greater than 99% deuteration in the 3 and 5 positions.

Preparation of Tritium-Labeled Compounds. (a) **2,4-Dimethyl-3-pentanone-*t*.** One gram of 2,4-dimethyl-3-pentanone was placed in a glass stoppered flask containing 0.1 ml of tritiated water (100 mCi/g), one pellet of sodium hydroxide and 15 ml of *p*-dioxane. This solution was stirred for 48 hr, then 20 ml of diethyl ether and 20 ml of water were added. The ketone was extracted into the ether layer, and the ether extracts were washed with water three times, dried with anhydrous magnesium sulfate, and evaporated to give the tritiated ketone.

(b) **3,5-Dimethyl-4-heptanone-*t*.** One gram of 3,5-dimethyl-4-heptanone was placed in a glass-stoppered flask containing 0.1 ml of tritiated water (100 mCi/g), 0.1 ml of sodium ethoxide, and 15 ml of *p*-dioxane. The solution was stirred for 24 hr. Then water and ether were added and the ketone was extracted into the ether layer, washed three times with water, dried with anhydrous magnesium sulfate, and evaporated to give the tritiated ketone.

Measurements of Rates of Bromination. For 2,4-dimethyl-3-pentanone and for 2,4-dideuterio-2,4-dimethyl-3-pentanone, the method reported earlier[6] was followed except that a Perkin-Elmer 202 UV-VIS spectrophotometer and 1-cm jacketed silica cells were used.

Stock solutions of ketone and (NaOH + NaOBr) were prepared. The concentrations of the reagents were ketone (0.4 *M*), hypobromite (4.0×10^{-3} *M*), and hydroxide ion (0.145 *M*). (NaOH + NaOBr) solution (1.5 ml) was placed in a jacketed silica cell and allowed to equilibrate. Ketone solution (0.01 ml) maintained at the reaction temperature was added rapidly into the cell and the contents stirred. Optical density measurements were taken at frequent intervals of time covering about 80% of the reaction. The infinity reading of the optical density was taken after 8–10 half-lives had elapsed.

As the concentration of the ketone $\ll$ [OH$^-$] and the hypobromite concentration is in excess the results were analyzed on the basis of pseudo-first-order kinetics. The good straight lines obtained by plotting log $(OD_t - OD_\infty)$ *vs.* time (where OD_t = optical density reading at time t and OD_∞ = the infinity reading of the optical density) justified this procedure. First-order rate constants were obtained from the slopes (m) of these lines. Ionization rate coefficients were calculated by using the equation

$$k^{H}_{OH^-} \text{ or } k^{D}_{OH^-} = 2.303m/[OH^-]$$

Six runs were made at each temperature. Table VI shows the data obtained in a typical run.

Table VI. Measurements of Rates of Bromination for $(CH_3)_2CHCOCH(CH_3)_2$ at 25°[a]

t, min	0	10	20	30	40	50	
Optical density	1.20	1.07	0.98	0.90	0.83	0.770	
t, min	60	70	80	90	100	110	∞
Optical density	0.71	0.67	0.63	0.60	0.57	0.54	0.40

[a] Initial concentration of ketone = 2.65×10^{-3} *M* and concentration of hydroxide ion = 0.144 *M*.

Since 3,5-dimethyl-4-heptanone is less water soluble than 2,4-dimethyl-3-pentanone, and reacted more slowly with OBr$^-$, the following procedure was adopted. Known volumes of standard sodium hydroxide solution and bromine were mixed in a 100-ml volumetric flask and were diluted to the mark with water. The concentrations of the components were selected so that the optical density at 330 nm was in the range 0.8–1.2 units. The ketone stock solution was prepared by dissolving a known weight of the ketone in 100 ml of water. The flask containing the stock solution of ketone and a flask containing 25 ml of the NaOBr solution were placed in a water bath thermostated at the desired temperature. After sufficient time for temperature equilibrium had elapsed, the reaction was initiated by transferring 10 ml of the ketone solution in the flask containing the NaOBr solution and shaking the contents. This solution (1.5 ml) was transferred into the jacketed cell maintained at the same temperature as the reaction mixture and the optical density was measured. Samples were withdrawn and optical density was measured at frequent, timed intervals convering about 80% of the reaction. The infinity reading of the optical density was taken after 8–10 half-lives had elapsed. The ionization rate coefficient was calculated by the method described above for 2,4-dimethyl-3-pentanone. Six runs were done at each temperature.

Measurements of Rates of D$^+$ Transfer. A stock solution of 2,4-dideuterio-2,4-dimethyl-3-pentanone was prepared by dissolving approximately 1 g of the ketone in 1 l. of water. Five hundred milliliters of this solution was placed in a flask and allowed to equilibrate in a water bath thermostated at 25°. A known volume of sodium hydroxide solution was added so as to make the final hydroxide ion concentration 0.1 *M*. Samples (50 ml) were withdrawn at frequent intervals of time and were injected into flasks containing ether and sufficient hydrochloric acid to neutralize the sodium hydroxide. The ketone was extracted into the ether layer which was then separated and dried over anhydrous $MgSO_4$. The ether was evaporated and the amount of 2,4-dideuterio-2,4-dimethyl-3-pentanone present in the ketone was analyzed by mass

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[6] J. R. Jones, R. E. Marks, and S. C. Subba Rao, *Trans. Faraday Soc.*, **63**, 111 (1967).

Table VII. Measurements of Rates of D^+ Transfer for $(CH_3)_2CDCOCD(CH_3)_2$ at 25°[a]

t, hr	0	2	4	6	8	10	12	14
% $(CH_3)_2CDCOCD(CH_3)_2$ in the ketone	99.2	81.5	66.8	55.0	45.0	36.7	30.5	25.0

[a] Concentration of the ketone = 8.62×10^{-3} *M* and concentration of the hydroxide ion = 0.095 *M*.

spectrometry; plots of log (2,4-dideuterio-2,4-dimethyl-3-pentanone) *vs.* time gave excellent straight lines. First-order rate constants were obtained from the slopes (m) of these lines and the ionization rate coefficients were calculated from the equation

$$k^{D}_{OH^-} = 2.303m/[OH^-]$$

Two runs were made. Table VII shows the data obtained in a typical run.

Measurements of Rates of T^+ Transfer. The procedure used was similar to the one reported previously,[2] but the low solubility of the ketones made it necessary to use very dilute solutions. Stock solutions of the ketone were prepared by dissolving 0.1 ml of the tritium labeled ketone in 1 l. of water. The stock solution of ketone (175 ml) was allowed to equilibrate in a thermostat. NaOH (15 ml of 2 *M*) maintained at the reaction temperature was added to the ketone solution. Samples (10 ml) were withdrawn at frequent intervals and injected into tubes containing sufficient hydrochloric acid for neutralization and 20-ml scintillator (2,5-diphenyloxazole in thiophene-free toluene). The ketone was extracted into the toluene layer which was then separated and dried over anhydrous $MgSO_4$. The solution (15 ml) was placed in a counting vial and counted. Samples were taken covering about 70% of the reaction. Plots of log (radioactivity) *vs.* time gave excellent straight lines. First-order rate constants were obtained from the slopes (m) of the lines and the ionization rate coefficients were calculated using the equation

$$k^{T}_{OH^-} = 2.303m/[OH^-]$$

Six runs were made at each temperature. Table VIII shows the data obtained in a typical run.

Table VIII. Measurements of Rates of T^+ Transfer for $(CH_3)_2CHCOCT(CH_3)_2$ at 25°[a]

t, min	0	25	50	75	100
Counts/4 min	182,380	146,923	120,230	99,950	78,520
t, min	125	150	175		
Counts/4 min	63,120	51,280	41,213		

[a] Concentration of the ketone = 0.87×10^{-3} *M* and concentration of hydroxide ion = 0.158 *M*.

Discussion

Since the substrates used in the current work can be considered as structural variations of acetone, a comparison of k_H/k_D for the reactions studied in this work with that for acetone[7] would be profitable. The values of k_H/k_D at 30° decrease in the order acetone > 2,4-dimethyl-3-pentanone > 3,5-dimethyl-4-heptanone as expected on the basis of the current theory of isotope effects. It has been suggested[8] that in a series of similar proton transfers, the primary isotope effect k_H/k_D would reach a maximum for the transfer with the most symmetrical transition state. Bell and Goodall[9] have related the departure from the symmetry of the transition state to the difference between the pK of the donor and that of the acceptor, $\Delta pK = [pK_{acid} - pK_{base}]$. A number of recent studies support this prediction.[10]

For the ketones studied in the current work pK_a values are not available. However, it is reasonable to assume on the basis of the electronic factors that pK_a (acetone $\simeq$ 20) < pK_a (2,4-dimethyl-3-pentanone) < pK_a (3,5-dimethyl-4-heptanone). Compared to acetone, 2,4-dimethyl-3-pentanone has four substituent methyl groups while 3,5-dimethyl-4-heptanone has two substituent ethyl and two methyl groups; these electron donating substituents increase the electron density at the reaction site thereby decreasing the acidity.

In the hydroxide catalyzed bromination of acetone (p$K \simeq 20$) a deuterium isotope effect $k_H/k_D = 8.57$ was obtained at 30° after correcting for secondary isotope effects. For 2,4-dimethyl-3-pentanone and for 3,5-dimethyl-4-heptanone no such correction is required since the secondary isotope effects due to replacement of hydrogen by deuterium on the carbon atom on the opposite side of the carbonyl group are expected to be small. Since the anion of acetone is a stronger base than hydroxide ion, the proton will be closer to the hydroxide ion in the transition state. Ketones of successively higher pK_a values cause increasingly unsymmetrical transition states and lead to decreasing values of the isotope effects. Thus the observed trend in the isotope effects can be qualitatively explained. However, other factors may also be operative. In particular, the large difference between k_H/k_D for acetone and that for the other ketones may be a result of a dynamic steric effect[2] created by rapid rotation of the methyl and ethyl groups in 2,4-dimethyl-3-pentanone and 3,5-dimethyl-4-heptanone. It is possible that in the transition state the C–H bond is bent rather than stretched. In such cases, as Westheimer[8] suggested, the zero-point energy lost in the transition state will be small because the vibration frequencies for bending are much smaller than those for stretching. This feature would be confirmed by low values of $E_D - E_H$. The observed values are in fact small and decrease in the order 2,4-dimethyl-3-pentanone < 3,5-dimethyl-4-heptanone.

Neither 2,4-dimethyl-3-pentanone nor 3,5-dimethyl-4-heptanone exhibit the features which should be present if tunneling occurred in these proton transfer reactions.

(a) Unusually large isotope effects. k_H/k_D at 25° for 2,4-dimethyl-3-pentanone and 3,5-dimethyl-4-heptanone are 6.09 and 3.67, respectively. These are normal values.

(b) A_D/A_H values outside the specific limit. The absolute rate theory predicts the limits $3^{-1/2} < A_D/A_H < 1$ or, if the reaction is a three-center one, $1/3 < A_D/A_H < 3$. The results (Table III) show that the frequency factor A_D/A_H is within the limit.

(c) $E_D - E_H > 1200$ cal mol^{-1}. The maximum values $E_D - E_H$ corresponds to the difference of zero-point energy for the stretching of the C–D and C–H bonds which is usually in the region of 1.1 kcal mol^{-1}. The $E_D - E_H$ values observed are less than 1.2 kcal mol^{-1}.

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[7] J. R. Jones, *Trans. Faraday Soc.*, **65**, 2138 (1969).

[8] F. H. Westheimer, *Chem. Rev.*, 61, 265 (1961).

[9] R. P. Bell and D. M. Goodall, *Proc. Roy. Soc., Ser. A*, **294**, 273 (1966).

[10] (a) J. L. Longridge and F. A. Long, *J. Amer. Chem. Soc.*, **89**, 1292 (1967); (b) A. J. Kresge, D. S. Sagatys, and H. L. Chen, *ibid.*, **90**, 4174 (1968); (c) J. E. Dixon and T. C. Bruice, *ibid.*, **92**, 905 (1970); (d) R. P. Bell and B. J. Cox, *J. Chem. Soc., B*, 194 (1970); (e) *ibid.*, 783 (1971).

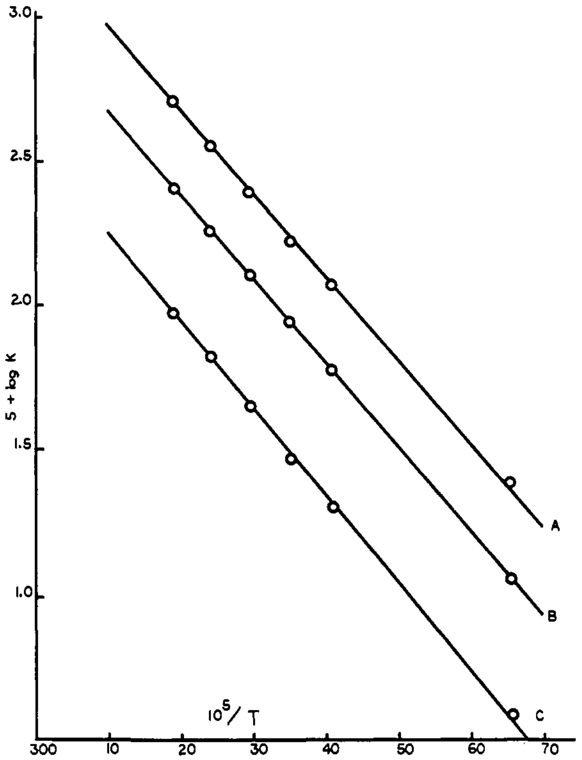


Figure 1. Plot of log ionization rate coefficient (l. sec^{-1} mol^{-1}) against $1/T$: (a) $(CH_3)_2CHCOCH(CH_3)_2$, (b) $(CH_3)_2CTCOCH(CH_3)_2$, (c) $(CH_3)_2CDCOCD(CH_3)_2$.

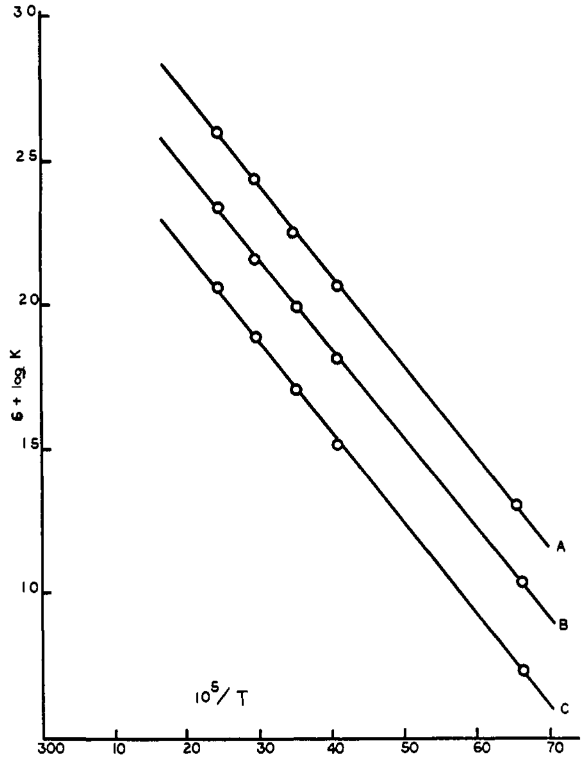


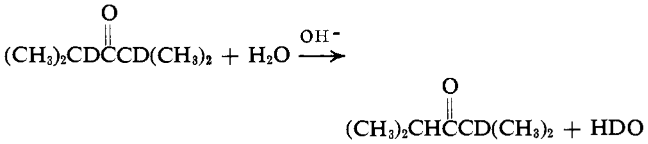
Figure 2. Plot of log ionization rate coefficients (l. sec^{-1} mol^{-1}) against $1/T$: (a) $CH_3CH_2CH(CH_3)COCH(CH_3)CH_2CH_3$, (b) $CH_3CH_2CT(CH_3)COCH(CH_3)CH_2CH_3$, (c) $CH_3CH_2CD(CH_3)COCD(CH_3)CH_2CH_3$.

(d) Curved Arrhenius plots. Curved Arrhenius plots may arise from a number of causes.[11] Curved Arrhenius plots are expected for simple proton-transfer reactions if there is quantum mechanical leakage of protons through the energy barrier opposing the reaction.[12]

All of our Arrhenius plots are linear (Figures 1 and 2). For the bromination of 2,4-dimethyl-3-pentanone a curved Arrhenius plot was reported[1] in contrast to our results. At temperatures below 25° there is good agreement between our results for the bromination of 2,4-dimethyl-3-pentanone and those published. At temperatures above 25° however, the rate constants obtained in the present work are smaller than the reported values. For the detritiation of 2,4-dimethyl-3-pentanone there is good agreement between our results and those reported[2] in the range 0–40°. However, the detritiation rates were not studied above 40° to investigate the sharp break observed in the previous study.

Tritium Isotope Effects. The most striking aspect of our work is that a deuterium isotope effect is observed while a tritium isotope effect is not. Further, the Arrhenius parameters for H^+ and T^+ transfers are similar.

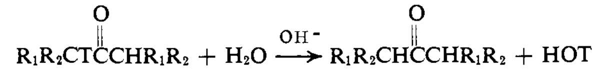
On the basis of Swain's equation,[13] $\log (k_H/k_T) = 1.442 \log (k_H/k_D)$, it is possible to expect a tritium isotope effect of 13.55 for 2,4-dimethyl-3-pentanone and 9.82 for 3,5-dimethyl-4-heptanone at 25°, in contrast to the current experimental findings. The absence of a tritium isotope effect led us to consider the possibility that in the base-catalyzed bromination of the bulky ketones investigated, bromination might not be a fast step and hence the measured rates of bromination may not represent the rates of proton transfer. In such a case, comparison of the rates of bromination and detritiation would not yield a true isotope effect. One way of examining such a possibility is to compare the rates of D^+ transfer obtained indirectly by bromination of $(CH_3)_2CDCOCD(CH_3)_2$ and directly by studying the deuterium–hydrogen exchange reaction



$$(CH_3)_2CD\overset{O}{\overset{\|}{C}}CD(CH_3)_2 + H_2O \xrightarrow{OH^-} (CH_3)_2CH\overset{O}{\overset{\|}{C}}CD(CH_3)_2 + HDO$$

The values for $k^D_{OH^-}$ at 25° obtained by bromination and those obtained by exchange reaction are 2.92×10^{-4} and 2.74 l. mol^{-1} sec^{-1}, respectively. The agreement is reasonably good and confirms that the rates of bromination represent the rates of D^+ transfer.

Another possible explanation for the absence of a tritium isotope effect is that the C–T bond cleavage may not be the rate determining step of the reaction



$$R_1R_2CT\overset{O}{\overset{\|}{C}}CHR_1R_2 + H_2O \xrightarrow{OH^-} R_1R_2CH\overset{O}{\overset{\|}{C}}CHR_1R_2 + HOT$$

It is possible that the tritium–hydrogen exchange takes place according to Scheme I. Inspection of the tritiated compounds used in the present work reveals the presence of one ionizable proton and one ionizable triton in each tritiated molecule. Since a C–T bond is stronger than a C–H bond, the C–H bond would be broken first and the carbanion thus formed exists mainly as the enolate ion.

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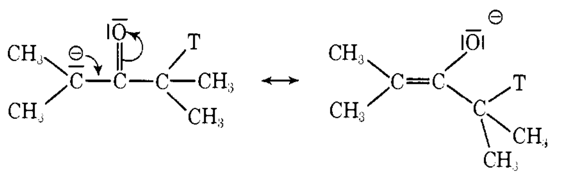
[11] J. R. Hullet, *Quart. Rev., Chem. Soc.*, **18**, 227 (1964).

[12] R. P. Bell, *Proc. Roy. Soc., Ser. A*, **148**, 241 (1935).

[13] C. G. Swain, E. S. Stivers, J. F. Reuwer, and L. J. Schaad, *J. Amer. Chem. Soc.*, **80**, 5855 (1958).



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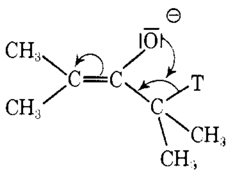
The enolate ion is a stronger base than hydroxide ion and also its proximity to tritium enables it to abstract the triton.

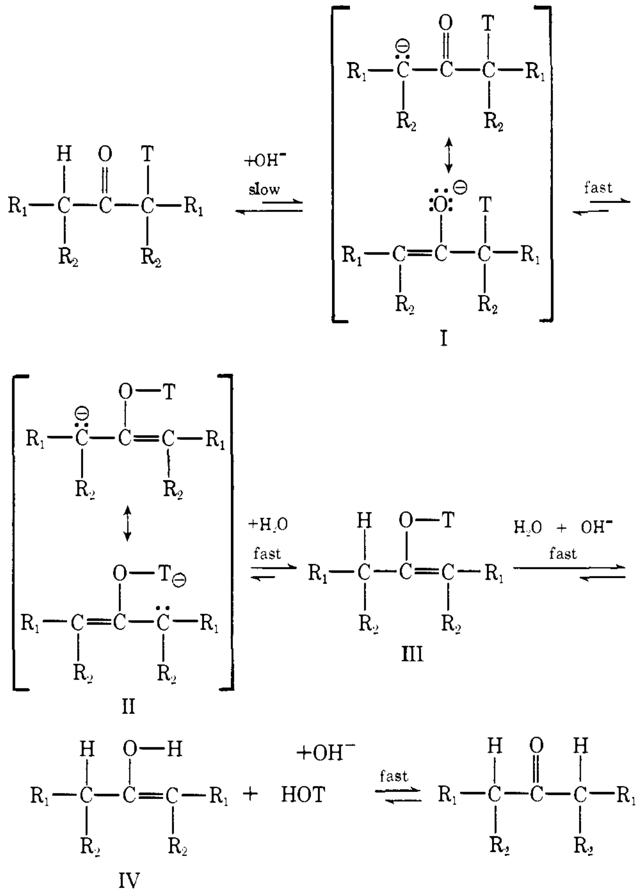


Finally, loss of tritium occurs from the enol form (III) to the hydroxide ion, and this is a fast step.

Thus the tritium–hydrogen exchange involves a rate determining proton transfer followed by loss of tritium in a fast step. In the detritiation experiments, what is being measured is the rate of proton transfer and not T^+. Hence it is not surprising to find no tritium isotope effect by comparing the rates of bromination and rates of detritiation. The observed Arrhenius parameters are also in accordance with this interpretation.

One of the referees disagrees with the above interpretation and has made an alternative suggestion for interpretation of the data. It seems more reasonable that the nonexistence of a tritium isotope effect is an experimental artifact, produced perhaps by complications such as those discussed by Lii and Miller.[14] The present study assumes the bromination reaction to be second order, but Lii and Miller[14] demonstrate third-order kinetics for the very same substrate. Lii and Miller did use a somewhat lower bromine concentration, but their result implies at least mixed second- and third-order processes under the conditions of the present study.

Scheme I



Acknowledgments. This research was supported by the U. S. Atomic Energy Commission under Contract No. AT(30-1)4254 to the Lincoln University.

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[14] R. R. Lii and S. I. Miller, *J. Chem. Soc. B*, 2269 (1971).