reactions of polyhalo-methanes and ethanes with aqueous base.

Our relatively large isotope effect shows that we are not plagued by the phenomenon apparently observed by Cram and Hine; *i.e.*, in the present case the carbanion-type intermediate clearly reacts sufficiently slowly with solvent that diffusion of solvent is not rate-determining.

Salts in cyclohexylamine are but slightly dissociated[15]; because of its comparative stability, our intermediate is probably not a free carbanion but is probably better described as a lithium alkyl. The further question of the more detailed description of such an organometallic derivative as a covalent compound or as "tight" or "loose" ion-pair is reserved for the discussion in Paper V.[16]

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[15] (15) Conductivity experiments of W. M. Padgett to be published shortly.

[16] (16) A. Streitwieser, Jr., D. E. Van Sickle and L. Reif, *J. Am. Chem. Soc.*, **84**, 258 (1962).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIF.]

Acidity of Hydrocarbons. IV. Secondary Deuterium Isotope Effects in Exchange Reactions of Toluene and Ethylbenzene with Lithium Cyclohexylamide[1]

BY A. STREITWIESER, JR.,[2] AND D. E. VAN SICKLE[3]

RECEIVED JUNE 21, 1961

Some secondary deuterium isotope effects were studied in the exchange reactions of hydrocarbons with lithium cyclohexylamide in cyclohexylamine; $k(C_6H_5CHDCH_3)/k(C_6H_5CHDCD_3) = 1.11 \pm 0.03$, a result that is interpreted to indicate that the transition state has substantial carbanionic character. $3k(C_6H_5CH_2D)/k(C_6H_5CD_3) = 1.31$; analysis of this result suggests that the leaving deuterium and perhaps a lithium are close to the central carbon at the transition state.

Despite the several continuing controversies regarding the detailed interpretation of some secondary deuterium isotope effects, sufficient data are now available to provide useful analogies in elucidating structural and electronic influences in transition states of some reactions.[4] It was with the hope of gathering useful information about the nature of the hydrocarbon moiety of the transition state for the proton exchange reaction with lithium cyclohexylamide in cyclohexylamine that studies were undertaken of some secondary deuterium isotope effects in this reaction.

A β-deuterium isotope effect was obtained with the use of ethylbenzene-α,β,β,β-d_4. This compound was obtained by the following sequence: acetophenone was repeatedly treated with D_2O and a trace of base to exchange the α-hydrogens. Reduction with lithium aluminum hydride gave 1-phenylethanol-2,2,2-d_3, which was converted to the chloride and reduced with lithium aluminum deuteride and lithium deuteride. The resulting hydrocarbon was mixed with ethylbenzene-α-*d* and the mixture was allowed to exchange with lithium cyclohexylamide in cyclohexylamine following our usual procedure.[5] Aliquots of the hydrocarbon were isolated at intervals and the relative amounts of the various deuterated ethylbenzenes present were determined by mass spectroscopy.[6]

An α-deuterium isotope effect was obtained through the use of toluene-α,α,α-d_3. This compound was prepared by reduction of benzotrichloride with zinc and acetic acid-*d*.[7] This material was mixed with toluene-α-*d* and this mixture was also allowed to exchange with lithium cyclohexylamide following our usual procedure. Samples of toluene were isolated at intervals and analyzed by mass spectroscopy.[6]

Results and Discussion

β-Deuterium Isotope Effect.—Replacement of the α-deuterium atom in ethylbenzene-α,β,β,β-d_4 gives ethylbenzene-β,β,β-d_3. In principle, the change in either reactant or product with time could be used to give a rate constant; however, because the methyl group was not fully deuterated, enough $-d_3$ compound is converted to $-d_2$ to make more reliable the determination of the rate constant by following the disappearance of $-d_4$. For the same reason we follow the appearance of $-d_0$ rather than the disappearance of $-d_1$ for determining the rate of reaction of ethylbenzene-α-*d*.

In Fig. 1, these changes are compared graphically. The $-CD_3$ group clearly slows the rate by about 10%.

Alternately, a point by point comparison may be effected by the use of eq. 1, in which the time has been eliminated.

$$\frac{k_{CH_3}}{k_{CD_3}} = \frac{\log \dfrac{D_0{}^0 - D_0{}^e}{D_0{}^t - D_0{}^e}}{\log \dfrac{D_4{}^0 - D_4{}^e}{D_4{}^t - D_4{}^e}} \qquad (1)$$

D_n refers to the percentage of $-d_n$ component in the ethylbenzene aliquot. This procedure yields $k_{CH_3}/k_{CD_3} = 1.11 \pm 0.03$.

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[1] (1) This work was supported by the United States Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command, under contract No. AF 49(638)-105. Reproduction in whole or in part is permitted for any purpose of the United States Government. This paper was presented in part at the Sixteenth National Organic Symposium of the American Chemical Society, Seattle, Wash., June, 1959.

[2] (2) Alfred P. Sloan Fellow.

[3] (3) Shell Development Co. Fellow, 1957–1958.

[4] (4) For recent reviews, see (a) L. Melander, "Isotope Effects on Reaction Rates," the Ronald Press Co., New York, N. Y., 1960, Chapt. 5; and (b) A. Streitwieser, Jr., *Ann. N. Y. Acad. Sci.*, **84**, 576 (1960).

[5] (5) A. Streitwieser, Jr., D. E. Van Sickle and W. C. Langworthy, *J. Am. Chem. Soc.*, **84**, 244 (1962).

[6] (6) We are greatly indebted to Dr. David P. Stevenson of the Shell Development Co., Emeryville, Calif., for the mass spectral analyses.

[7] (7) R. Renaud and L. C. Leitch, *Can. J. Chem.*, **34**, 98 (1956).

These treatments assume that only the α-hydrogens can exchange. This question was examined by a study of ethylbenzene-β-*d* which was found to be completely stable to conditions considerably more drastic than those used in the present study.[8]

An impressive amount of data has accumulated to show that deuterium effectively has an electron-donating inductive effective relative to hydrogen.[4b] Part of the evidence comes from isotope effects in quadrupole coupling constants and n.m.r. chemical shifts in alkyl halides,[9] dipole moment differences between deuterium and protium compounds,[10] and optical activity resulting from hydrogen–deuterium asymmetry. Of especial importance to the present work, however, are the substantial changes in acidity resulting from deuterium substitution. Some recent determinations are summarized in Table I.

TABLE I

DEUTERIUM ISOTOPE EFFECTS OF ACIDITY

Acid	k_H/k_D	Ref.
$C_6H_5CD_2COOH$	1.12 ± 0.02	11
C_6D_5COOH	1.024 ± .006	12
C_6D_5OH	1.12 ± .02	12
DCOOH	1.06 ± .03	13
	1.12 ± .05	14
CD_3COOH	1.033 ± .002	15

Although the detailed source of the effects observed is apparently still not definitely settled,[16] the data show definitely that deuterated acids are significantly less acidic than the corresponding protium acids and allow us to make rough predictions of the expected magnitudes of the effects in other systems. For this purpose, the measurements of benzoic and acetic acids are probably the most accurate, having been done by the conductivity method. In the deuterated acetate ion, each deuterium is separated by two atoms from the atom bearing the negative charge and causes about a 1% decrease in acidity. Deuteriums one atom closer might be expected to have about three times the effect, on the basis of the usual pattern of inductive changes and intramolecular distance. On this basis, we expect a single deuterium in formic acid to lower the acidity by ~4%, a figure just slightly lower than those reported by Ropp[13] and by Bell and Jensen.[14]

The three deuteriums in the α-phenylethyl-β,β,β-d_3 anion are also separated by one atom from the carbon bearing most of the negative charge; accordingly, we would anticipate a reduction in the acidity of the corresponding hydrocarbon by ~12%. This type of comparison is certainly crude, but the results should be of the correct order of magnitude. The observed effect on the rate of exchange is close to this expected effect on acidity. The argument is clearly not rigorous, but the observed isotope effect strongly suggests that the hydrocarbon moiety has acquired substantial negative charge at the transition state of this exchange reaction.[17]

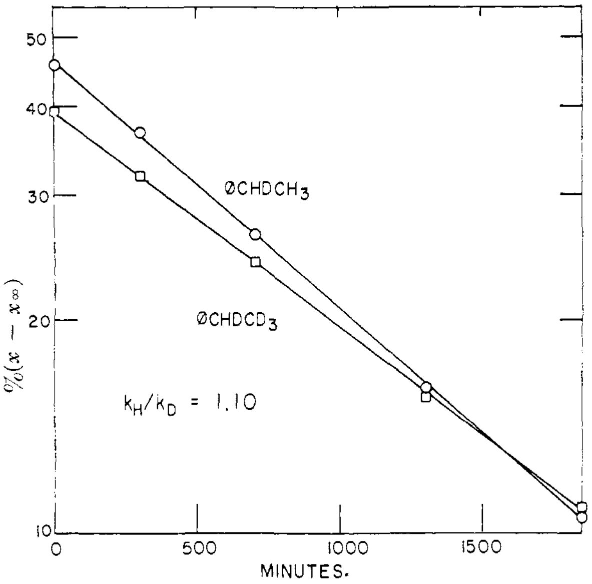

Fig. 1.—β-Deuterium isotope effect for exchange of ethylbenzene-α,β,β,β-d_4 and ethylbenzene-α-*d* with lithium cyclohexylamide in cyclohexylamine at 49.9°.

α-Deuterium Isotope Effect.—For this case, the total reaction is

$$\underset{D_3}{C_6H_5CD_3} \underset{k_{-3}}{\overset{3k_3}{\rightleftarrows}} \underset{D_2}{C_6H_5CHD_2} \underset{2k_{-2}}{\overset{2k_2}{\rightleftarrows}} \underset{D_1}{C_6H_5CH_2D} \underset{3k_{-1}}{\overset{k_1}{\rightleftarrows}} \underset{D_0}{C_6H_5CH_3} \qquad (2)$$

There are four possible species present which are interrelated by six rate constants. The two of interest here are k_1 and k_3, which, by the assumption of the equilibrium constant being equal to unity,[5] are the same as k_{-1} and k_{-3}, respectively.[18]

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(8) Unpublished experiments of Dr. S. Suzuki.

(9) J. Duchesne, *J. Chem. Phys.*, **20**, 1804 (1952); **25**, 369 (1956); J. Duchesne, A. Monfils and J. Garson, *Physica*, **22**, 816 (1956); J. W. Simmons and J. H. Goldstein, *J. Chem. Phys.*, **20**, 122 (1952); S. L. Miller, L. C. Aamodt, G. Dousmanis, C. H. Townes and J. Kraitchman, *ibid.*, **20**, 1112 (1952); G. V. D. Tiers, *J. Am. Chem. Soc.*, **79**, 5585 (1957).

(10) C. P. Smyth and J. M. A. de Bruyne, *ibid.*, **57**, 1203 (1935); R. P. Bell and I. E. Coop, *Trans. Faraday Soc.*, **34**, 1209 (1938); D. R. Lide, Jr., *J. Chem. Phys.*, **33**, 1519 (1960).

(11) E. A. Halevi and M. Nussim, *Bull. Res. Council Israel*, **5A**, 263 (1956).

(12) H. S. Klein and A. Streitwieser, Jr., *Chemistry & Industry*, 180 (1961).

(13) G. A. Ropp, *J. Am. Chem. Soc.*, **82**, 4252 (1960).

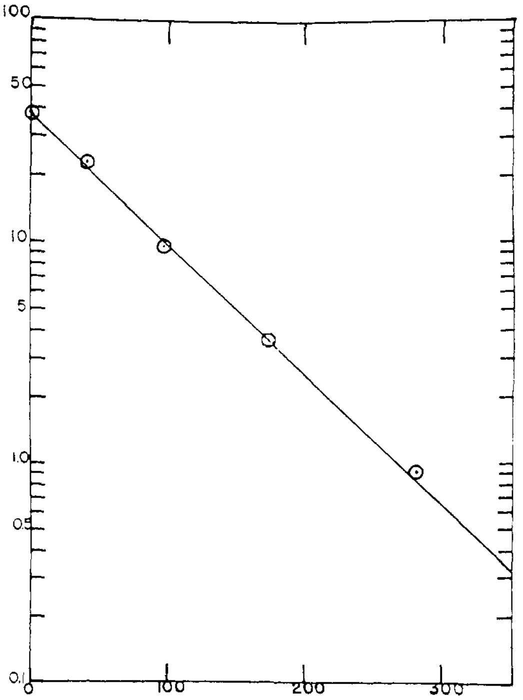
(14) R. P. Bell and M. B. Jensen, *Proc. Chem. Soc.*, 307 (1960).

(15) H. S. Klein, unpublished results.

(16) See, for example, the arguments of R. E. Weston, Jr., *Tetrahedron*, **6**, 31 (1959), and E. A. Halevi and M. Nussim, *Tetrahedron*, **5**, 352 (1959).

(17) The above discussion neglects the possible isotope effect associated with hyperconjugation. β-Deuterium atoms diminish the stability of carbonium ions; the effect has been attributed to reduced hyperconjugative stabilization (for summaries, see E. S. Lewis, *Tetrahedron*, **5**, 143 (1959) and V. J. Shiner, Jr., *ibid.*, **5**, 243 (1959)). The evidence for anionic hydrogen hyperconjugation is limited; such effect is probably not important in our case. Of potentially greater significance, however, is L. S. Bartell's [*Tetrahedron Letters*, **No. 6**, 13 (1960)] interpretation of the β-deuterium effect. Essentially, this argument says that diminished non-bonding repulsions between the leaving group and a β-hydrogen in the transition state lowers a bending force constant for the latter. A deuterium atom is unable to benefit as much from such freedom and an isotope effect results. This explanation would apply as well to our carbanion case as to carbonium ions. Nevertheless, if this effect does apply, the result of the interpretation is unchanged, namely, that the transition state of our exchange reaction is well on its way to carbanionic character.

(18) Actually, isotope effects may make small differences in these equilibrium constants; however, in the equations to follow, k_{-1} and k_{-3} are used in relatively small correction terms for the back reactions and this approximation will not result in significant error.



$\theta - {}^1/_3 \int_0^t \rho\,(D_2/D_3)\mathrm{d}t$, minutes.

Fig. 2.—Evaluation of k_3.

Because of the growing deuterium content of solvent during reaction, each equation actually represents pseudo-second-order kinetics. Such a system of consecutive second-order reversible reactions yields a set of differential equations which cannot be solved analytically in the general case. However, by use of the elegant approach of Widequist,[19] a particular integration of the data defines a new time scale, in terms of which the solution reduces to first order.

The disappearance of D_3 is given as

$$-\,\mathrm{d}D_3/\mathrm{d}t = 3k_3D_3(1-\rho) - k_{-3}D_2\rho \qquad (3)$$

in which $D_j = [C_6H_5CH_{3-j}D_j]$, and the other symbols have the meaning assigned previously.[5] Inserting $k_{-3} = k_3$ and rearranging gives

$$-\,\mathrm{d}D_3/D_3 = 3k_3(1-\rho)\mathrm{d}t = k_3(D_2/D_3)\rho\mathrm{d}t \qquad (4)$$

Following Widequist,[19] we now define

$$\theta = t - \int_0^t \rho\mathrm{d}t \qquad (5)$$

We substitute in eq. 4 and integrate to obtain

$$\ln D_3^0/D_3^t = 3k_3\,[\theta - 1/3\int_0^t \rho(D_2/D_3)\mathrm{d}t] \qquad (6)$$

Since ρ, and therefore θ, are rather complicated functions of time and the deuterated species reacted, it is convenient to evaluate graphically the integrals on the right side of eq. 6. The quantity ρ is calculated from its definition[5] and the assumption that all deuterium removed from the toluenes after time t is present as R'NHD. The values of the integrals, $\int_0^t \rho\mathrm{d}t$ and $\int_0^t \rho(D_2/D_3)\mathrm{d}t$, are obtained by plotting ρ and $\rho D_2/D_3$, respectively, against t and taking the areas with a planimeter up to the appropriate times. The results are summarized in Table II.

TABLE II

EVALUATION OF INTEGRALS FOR k_3

Time, min.	$10^{-4}\,\rho$	θ, min.	$\int_0^t \rho(D_2/D_3)\mathrm{d}t$, min.
0	0	0	0
40	90	39.8	0.15
100	218	98.2	1.4
180	322	174.9	8.0
300	415	288.7	22.4
800	497	754.4	338

A plot of the right hand side of eq. 6 against the percentage D_3 on a semi-log scale gives a straight line of slope $3k_3$ (Fig. 2). The value so derived is $k_3 = 4.56 \times 10^{-3}$ min.$^{-1}$.

The rate of formation of D_0 is given by

$$\mathrm{d}D_0/\mathrm{d}t = k_1D_1(1-\rho) - 3k_{-1}\rho D_0 \qquad (7)$$

We assume $k_1 = k_{-1}$, rearrange and integrate, giving

$$\int \frac{\mathrm{d}D_0}{(1-\rho)D_1} = k_1[t - 3\int_0^t \frac{\rho}{1-\rho}\frac{D_0}{D_1}\mathrm{d}t] \qquad (8)$$
$$= k_1\varphi$$

The integrals are again evaluated graphically, giving the quantities summarized in Table III.

TABLE III

EVALUATION OF INTEGRALS FOR k_1

Time, min.	$\int_0^t \frac{\mathrm{d}D_0}{(1-\rho)D_1}$	φ, min.
0	0	0
40	0.216	39.8
100	0.593	97.4
180	1.020	170.8
300	1.580	265.8
800	2.64	434.3

A plot of the left side of eq. 8 *vs.* φ gives a straight line of slope k_1 (Fig. 3); $k_1 = 6.0 \times 10^{-3}$ min.$^{-1}$.

Finally, k_2 may be evaluated in a completely analogous way. The rate equation is

$$\mathrm{d}D_2/\mathrm{d}t = 3k_3D_3(1-\rho) + 2k_{-2}D_1\rho - 2k_2D_2(1-\rho) - k_3D_2\rho \qquad (9)$$

The value obtained for $k_2 = k_{-2}$ is 5.45×10^{-3} min.$^{-1}$, but is undoubtedly considerably less accurate than the values for k_1 and k_3.

The secondary isotope effect is given by $k_1/k_3 = 1.31$; *i.e.*, substitution of two deuteriums on a methyl group diminishes the rate of exchange of a third deuterium by 24%. It is difficult to assign a probable error to this number, although the fine definition of the final lines renders improbable an error of more than a few per cent. We would expect $k_1/k_2 = k_2/k_3$. The actual ratios, 1.10 and 1.19, respectively, are only in fair agreement with this thought and reflect the larger errors that creep into the more complex evaluation of k_2.

The interpretation of these numbers requires the quantitative assessment of several factors. With the present state of knowledge about secondary deuterium isotope effects, this dissection cannot be done exactly. By analogy with other systems, useful conclusions can be reached concerning the mechanism of the present reaction. We must em-

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(19) S. Widequist, *Acta Chem. Scand.*, **4**, 1216 (1950); *Arkiv. Kemi*, **8**, 545 (1956). We are greatly indebted to Professor R. E. Powell for telling us about this method.

phasize, however, that these conclusions should not be considered as a rigorously logical outcome, but should be classed rather as "reasonable" or "strongly suggestive."

The magnitude of our α-deuterium secondary isotope effect is similar to those observed in several other systems. Examples are the effects of α-deuteriums on solvolytic displacement reactions,[20] the pseudo-basicity of α-deuterated benzhydrols[21] and *cis-trans* isomerization and addition reactions of deuterium-substituted olefins.[22] In the accepted explanation for this isotope effect, a hydrogen bending vibration becomes an out-of-plane bending vibration of lower frequency in the flatter transition state of lower coördination. The greater mass of deuterium produces a smaller frequency change and an isotope effect results. In limiting solvolyses, for example, k_H/k_D for a single α-deuterium is typically around 1.15. This value is substantially lower than that calculated for complete conversion from a tetrahedral four-coördinated carbon to a trigonal three-coördinated carbon, $\sim$1.4.[20a] The difference has been attributed to the effect that the juxtaposed leaving group still has on the bending vibration of the α-hydrogen in the transition state; this explanation finds support in the reduced isotope effect in nucleophilic solvolyses and direct displacement reactions.[20a,d] However, it should be noted that in all of these cases, the central carbon atom has carbonium ion character. From the electron-donating "inductive effect" of deuterium (*vide supra*) we would expect an α-deuterium to stabilize a carbonium ion in the absence of other effects. Such stabilization of carbonium ions has been reported for favorable cases.[12,21,23] This effect works against the out-of-plane vibration effect and tends to reduce k_H/k_D. In our carbanion case, however, both effects work in the same direction. By extrapolation of the β-isotope effect in the exchange reaction of ethylbenzene (*vide supra*), we would anticipate the "inductive effect" of two α-deuteriums in toluene to produce a k_H/k_D of up to $\sim$1.20. This leaves only a k_H/k_D $\sim$1.10 to be attributed to the out-of-plane bending vibration effect of *two* α-deuteriums. We conclude, therefore, that either the reaction has not proceeded far at the transition state or that this vibration is still impeded substantially by nearby atoms at the transition state. Since the effect of methyl groups on the reaction[24] and the β-deuterium isotope effect (*vide supra*) strongly suggest that the transition state is well along to flat carbanion character, we can suggest that nearby atoms are responsible and that these atoms are both the leaving proton and the lithium of the lithium cyclohexylamide catalyst. This interpretation is completely consistent with the four-center transition state picture I that emerges from the stereochemistry of the exchange reaction and is discussed further in the following paper.

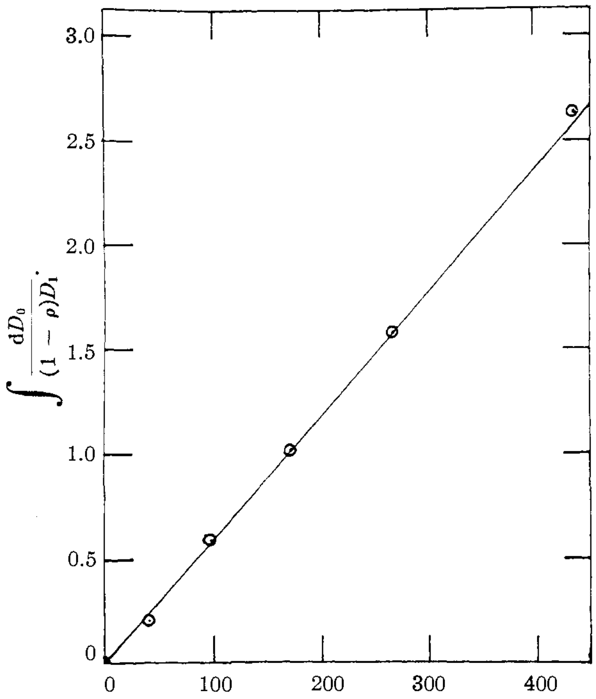
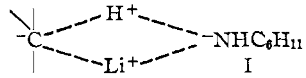


Fig. 3.—Evaluation of k_1.



I

Experimental

Ethylbenzene-α,β,β,β-d_4.—Acetophenone-α,α,α-d_3[25] was reduced to the alcohol in the usual way with lithium alu-

TABLE IV

EXCHANGE EXPERIMENT WITH $C_6H_5CHDCD_3$ + C_6H_5-$CHDCH_3$, 49.9°

$a = 0.48, c = 0.067$

Time, min.	Component, %				
	D_4	D_3	D_2	D_1	D_0
0	41.8	6.55	0.48	48.9	2.17
300	34.4	12.8	1.37	39.9	11.4
700	26.8	19.7	2.48	29.6	21.3
1300	18.0	27.3	3.16	19.28	31.7
1850	13.47	31.4	4.15	13.85	37.1
7500	2.52	40.9	5.39	3.15	47.9

TABLE V

EXCHANGE OF $C_6H_5CH_2D$ + $C_6H_5CD_3$, 49.9°

$a = 0.49, c = 0.070$

Time, min.	Component, %			
	D_3	D_2	D_1	D_0
0	37.0	10.9	47.0	5.1
40	22.7	19.4	43.2	14.7
100	9.5	19.3	40.9	30.3
180	3.6	13.1	36.6	46.7
300	0.9	6.3	28.2	64.7
800	0.06	0.94	13.7	85.3

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[20] (a) A. Streitwieser, Jr., R. H. Jagow, R. C. Fahey and S. Suzuki, *J. Am. Chem. Soc.*, **80**, 2326 (1958); (b) W. H. Saunders, Jr., S. Asperger and D. H. Edison, *ibid.*, **80**, 2421 (1958); (c) K. Mislow, K. S. Borcic and V. Prelog, *Helv. Chim. Acta*, **40**, 2477 (1957); (d) R. R. Johnson and E. S. Lewis, *Proc. Chem. Soc.*, 52 (1958); (e) H. S. Klein, unpublished results.

[21] R. Stewart, A. L. Gatzke, M. Mocek and K. Yates, *Chemistry & Industry*, 331 (1959).

[22] S. Seltzer, *J. Am. Chem. Soc.*, **83**, 1861 (1961); D. B. Denney and N. Tunkel, *Chemistry & Industry*, 1383 (1959).

[23] V. J. Shiner, *J. Am. Chem. Soc.*, **82**, 2655 (1960).

[24] A. Streitwieser, Jr., and D. E. Van Sickle, *ibid.*, **84**, 249 (1962).

[25] Our procedure for the preparation of this compound by exchange of acetophenone with D_2O has been published previously: D. S. Noyce, G. L. Woo and M. J. Jorgenson, *J. Am. Chem. Soc.*, **83**, 1160 (1961).

minum hydride.[26] The product (30 g.) was refluxed for several hours with 47 g. of thionyl chloride in 185 ml. of toluene. After removal of solvent and excess thionyl chloride, the residue was fractionated to yield 18.5 g. (50%) of α-phenethyl-β,β,β-d_3 chloride, b. 60–61° (8 mm.).

A solution of 12 g. of this chloride in 75 ml. of tetrahydrofuran was refluxed for 12 hours with 0.5 g. of lithium aluminum deuteride and 1.5 g. of lithium deuteride. Excess deuteride was destroyed with water and the mixture was taken up in pentane. Washing, drying and distilling gave 7.8 g. (82%) of ethylbenzene-α,β,β,β-d_4, b. 133–135°, $n^{25.5}\text{D}$ 1.4918.

Kinetics.—Two experiments were performed using the sealed tube procedure (A).[5] In the first, a mixture of ethylbenzene-α-d and ethylbenzene-α,β,β,β-d_4 was run at 49.9° as a 0.48 M solution in cyclohexylamine having a formal concentration of 0.067 M in lithium cyclohexylamide. Tubes were removed from the thermostat at intervals and the ethylbenzene was removed, distilled and examined by mass spectral analysis.[6] The results are given in Table IV.

In the second experiment, a mixture of toluene-α-d and toluene-α,α,α-d_3[7] was handled in the same way. The results are summarized in Table V. The rate constants obtained as discussed above are given as k_{exp}. The $2b/Q$ correction[5] has not been applied, since the desired quantities are rate ratios.

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(26) We are indebted to G. W. Burton for this preparation.

[Contribution from the Department of Chemistry, University of California, Berkeley, Calif.]

Acidity of Hydrocarbons. V. Stereochemistry and Mechanism of the Proton Exchange Reactions of Hydrocarbons in Cyclohexylamine[1]

By A. Streitwieser, Jr.,[2] D. E. Van Sickle[3] and L. Reif

Received June 21, 1961

The rate of racemization of optically active ethylbenzene-α-d with lithium cyclohexylamide in cyclohexylamine at 49.9° is 2.8 times the loss of deuterium. This result is analyzed to show that replacement of the α-hydrogen by hydrogen in this system proceeds with 82% net retention of configuration. A mechanism of the exchange reaction is proposed which involves a four-membered ring transition state in which specific asymmetric solvation by individual solvent molecules is not necessary to accommodate the results.

Of especial significance for the elucidation of the mechanism of a reaction is the stereochemistry. Determination of the stereochemistry of a proton exchange reaction can be accomplished in principle by a comparison of a rate of stereochemical change with a rate of isotope exchange; all such procedures require some knowledge of isotope effects. In the present study in which a knowledge of isotope effects is still required, we examine instead the stereochemistry of replacement of an *α-hydrogen* by *hydrogen* in optically active ethylbenzene-α-d.

Results and Discussion

Optically active ethylbenzene-α-d[4] was allowed to react with lithium cyclohexylamide in cyclohexylamine at 49.9°. At intervals, aliquots of the hydrocarbon were isolated and examined both for deuterium content and for optical activity. A semi-log plot of optical activity against time gave a satisfactory straight line corresponding to $k_{\text{rac}} = 3.0 \times 10^{-5}$ sec.$^{-1}$, whereas a corresponding plot of deuterium content minus the equilibrium value gives $k_{\text{D}_{\text{exp}}} = 1.20 \times 10^{-5}$ sec.$^{-1}$. The latter value must be corrected for the back reaction as detailed earlier[5] to give the true pseudo-first-order rate constant for the forward step, $k_{\text{D}} = 1.07 \times 10^{-6}$ sec.$^{-1}$.[6]

Racemization under these conditions can result both from replacement of D by H and in part by replacement of H by H. The first case is trivial; we are interested in the fraction, λ, of the latter replacements, k_{H}, that result in racemization.

$$k_{\text{rac}} = k_{\text{D}} + \lambda k_{\text{H}} \qquad (1)$$

λ equals 0 for complete retention of configuration, $\lambda = 1$ if each replacement occurs with complete racemization and $\lambda = 2$ for inversion of configuration. The inequality of the experimental k_{rac} and k_{D} tell us immediately that $\lambda \neq 0$, but a more complete characterization requires a knowledge of k_{H}. This quantity cannot be measured directly but may be approximated from k_{D} and the isotope effects. A measurement of the deuterium–tritium isotope effect led to $k_{\text{H}}/k_{\text{D}} = 12 \pm 2$,[8] in which k_{H} here refers to ethylbenzene itself. The α-deuterium atom in ethylbenzene-α-d, however, is expected to slow down the rate of replacement of the hydrogen by a factor of 1.14 as estimated from the relative rates of toluene-α-d and toluene-α,α,α-d_3.[9] Hence, in the present case, k_{H} is estimated as $(12 \pm 2)k_{\text{D}}/1.14 = (11 \pm 2) \times 10^{-5}$ sec.$^{-1}$. Insertion of this value into eq. 1 gives $\lambda = 0.18 \pm 0.03$; *i.e.*, the lithium cyclohexylamide-catalyzed exchange of hydrogen by hydrogen in ethylbenzene-α-d occurs with 82 ± 3% net retention of configuration.

Previous studies[8] have demonstrated that the exchange reaction involves an intermediate of the alkyllithium or carbanion type. We can now eliminate free carbanions as the only intermediates in the reaction since resonance-stabilized benzylic anions are expected to be planar and incapable of supporting asymmetry. The reaction of the alkyl-

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(1) This work was supported by the United States Air Force through the Air Force Office of Scientific Research of the Air Research and Development Command, under contract No. AF 49(638)-105. Reproduction in whole or in part is permitted for any purpose of the United States Government. This paper was presented in part at the Sixteenth National Organic Symposium of the American Chemical Society, Seattle, Wash., June, 1959. A preliminary communication has been published: A. Streitwieser, Jr., D. E. Van Sickle and L. Reif, *J. Am. Chem. Soc.*, **82**, 1513 (1960).

(2) Alfred P. Sloan Fellow.

(3) Shell Development Co. Fellow, 1957–1958.

(4) E. L. Eliel, *J. Am. Chem. Soc.*, **71**, 3970 (1949).

(5) A. Streitwieser, Jr., D. E. Van Sickle and W. C. Langworthy, *ibid.*, **84**, 244 (1962).

(6) This rate constant is included in Table I of ref. 7.

(7) A. Streitwieser, Jr., and D. E. Van Sickle, *ibid.*, **84**, 249 (1962).

(8) A. Streitwieser, Jr., W. C. Langworthy and D. E. Van Sickle, *ibid.*, **84**, 251 (1962).

(9) A. Streitwieser, Jr., and D. E. Van Sickle, *ibid.*, **84**, 254 (1962).