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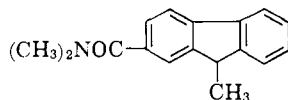
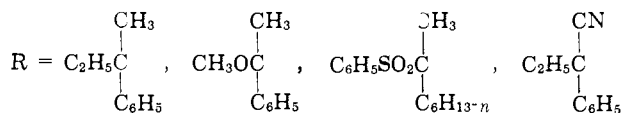
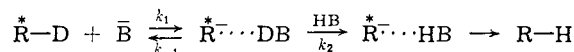
Electrophilic Substitution at Saturated Carbon. XXII. Intramolecular Hydrogen Transfer Reactions in Base-Catalyzed Allylic Rearrangements¹

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RECEIVED JUNE 1, 1964

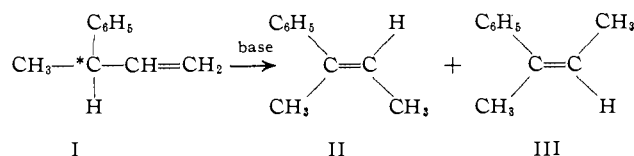
The base-catalyzed rearrangement of 3-phenyl-1-butene (*I-h*) to *cis*-2-phenyl-2-butene (II) in a variety of media containing deuterium donors (ROD) has been studied, as has the rearrangement of 3-phenyl-1-butene-3-*d* (*I-d*) in media containing proton donors. Intramolecularity in this hydrogen migration varied from a high of 56% with *I-h* in triethylcarbinol-*O-d* with potassium triethylcarboxide as base to a low of 6% obtained with *I-d* in *tert*-butyl alcohol with tetramethylammonium hydroxide as base. Other solvent systems studied were 1,2-dimethoxyethane 4.9 *M* in *tert*-butyl alcohol, *tert*-butyl alcohol, ethylene glycol, and their deuterated counterparts, as well as 91% dimethyl sulfoxide-9% methanol. Considerably higher intramolecularity was observed when hydrogen was rearranged than when deuterium was involved, factors of 2.5 to 3.5 being observed. The rates of isomerization varied by about 10⁵, being fastest in dimethyl sulfoxide-methanol-potassium methoxide, and slowest in ethylene glycol-potassium ethylene glycoxide. Estimated isotope effects for rearrangement varied from a low of $k_H/k_D = 1$ in ethylene glycol at 145° to 6 in 1,2-dimethoxyethane 4.9 *M* in *tert*-butyl alcohol at 50°. Only minor amounts of *trans*-2-phenyl-2-butene (III) were produced in the rearrangements. In dimethoxyethylene 4.9 *M* in *tert*-butyl alcohol-*O-d*, *I-h* gave II (cis-olefin) with 51% intramolecularity and III (*trans*-olefin) with 50% intramolecularity. In ethylene glycol-*O-d*, *I-h* gave II with 31% and III with 33% intramolecularity. The rates of hydrogen-deuterium exchange of II and III were demonstrated to be one to two powers of ten slower than the isomerization of I under the same conditions. Degradative experiments demonstrated that when *I-h* was isomerized to II in deuterated solvents, all of the deuterium introduced was in the 4-position of 2-phenyl-2-butene (II). In all runs, optically active I was employed, and the reactions were interrupted before isomerization was complete. Isotopic exchange of I was one to over two powers of ten slower than isomerization in all media. In *tert*-butyl alcohol-*O-d* (potassium *tert*-butoxide as base), (-)-*I-h* underwent isotopic exchange at a rate at least ten times faster than racemization, both rates being vastly slower than the isomerization rate. Thus exchange occurs with high retention of configuration. In ethylene glycol-*O-d* (potassium ethylene glycoxide as base), (-)-*I-h* racemized faster than it exchanged by a factor of 1.4. In this solvent, exchange went with net inversion. These results are interpreted in terms of allylic, ambident carbanions as intermediates, which are hydrogen bonded at both sites to the molecule of hydroxyl compound formed by abstraction of hydrogen or deuterium from starting material. The degree of intramolecularity is controlled by the relative rates of collapse of this material to rearranged olefin, and of isotopic exchange with solvent. The stereochemistry of exchange is controlled by whether isotopic exchange of this hydrogen-bonded intermediate occurs at the front or back face of the ambident anion.

Previous studies in this series established that, in the systems formulated, carbanions can be generated and destroyed by transfer of the same proton, first to base and then back to carbon, faster than other processes occur.² In terms of the kinetic scheme, $k_{-1} > k_2$. Evidence for such a relationship of rates was found in low and even negative isotope effects for the isotopic exchange reaction,^{2a,b} and in stereochemical results where rotation of cations^{2c} or anions^{2d} within ion-pairs occurred faster than ion-pair dissociation or substitution.



A clear implication of $k_{-1} > k_2$ is that in a system such as I, which has a driving force for allylic rearrangement to II or III, an intramolecular base-cata-

lyzed proton transfer in the presence of a deuterium pool in the medium is a distinct possibility. Accordingly, the rearrangement of I has been investigated in a variety of media and bases.



Following the announcement that compound I did indeed rearrange to II by intramolecular base-catalyzed proton transfer in *tert*-butyl alcohol-*O-d*-potassium *tert*-butoxide,³ other investigators reported examples of base-catalyzed intramolecular proton transfers in other allylic systems.⁴

System I possesses a number of advantages for systematic study of the proton transfer reaction: (1) The reaction $\text{I} \rightarrow \text{II} + \text{III}$ is irreversible; (2) compounds II and III undergo base-catalyzed isotopic exchange at rates much slower than the rearrangement of I; (3) olefin I is acidic enough to allow rearrangement to be investigated in all types of solvents with most kinds of bases; (4) the asymmetric center in I provides a means of study of the relative rates of racemization and isotopic exchange at the asymmetric center, and

(1) This research was supported by the Directorate of Chemical Sciences, Air Force Office of Scientific Research Grant No. AF-AFOSR-124-63. The authors wish to express their thanks for this support.

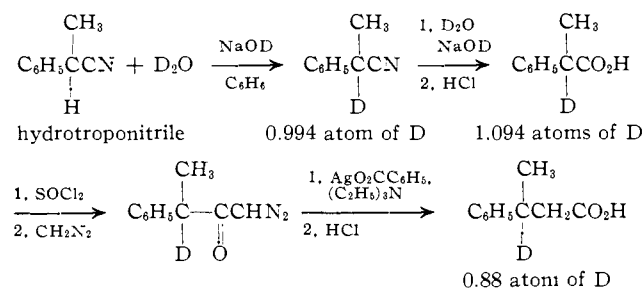
(2) (a) D. J. Cram, C. A. Kingsbury, and B. Rickborn, *J. Am. Chem. Soc.*, **83**, 3688 (1961); (b) D. J. Cram, D. A. Scott, and W. D. Nielsen, *ibid.*, **83**, 3696 (1961); (c) D. J. Cram and L. Gosser, *ibid.*, **85**, 3890 (1963); (d) *ibid.*, **86**, 5445 (1964).

(3) D. J. Cram and R. T. Uyeda, *ibid.*, **84**, 4358 (1962).

(4) (a) S. Bank, C. A. Rowe, Jr., and A. Schriesheim, *ibid.*, **85**, 2115 (1963); (b) W. von E. Doering and P. P. Gaspar, *ibid.*, **85**, 3043 (1963); (c) G. Bergson and A. M. Weidler, *Acta Chem. Scand.*, **17**, 862, 1798 (1963); (d) R. B. Bates, R. H. Carnighan, and C. E. Staples, *J. Am. Chem. Soc.*, **85**, 3032 (1963).

of how these rates compare with that of the allylic rearrangement.

Starting Materials.—Optically active 3-phenyl-1-butene ((+)-I-*h*), *cis*-2-phenyl-2-butene (II), *trans*-2-phenyl-2-butene (III), and 2-phenyl-1-butene (IV) were prepared as in previous studies.^{5,6} Optically active 3-deuterio-3-phenyl-1-butene ((+)-I-*d*) was prepared from 3-deuterio-3-phenylbutyric acid by the same method used for its protium counterpart.³ The acid was prepared by the sequence outlined below. Although hydrotroponitrile was almost completely deuterated in the α -position, and this isotope was completely retained upon hydrolysis in deuterium oxide, deuterium dropped to 0.88 atom of deuterium per molecule upon homologation by the Arndt-Eistert synthesis. This loss probably occurred after the preparation of the diazoketone, and was catalyzed by the base used to convert the diazoketone to the rearranged ester. When the reaction was run on a small scale, the deuterium loss was negligible.



Isomerization Reactions.—The general character of the isomerization reaction was investigated by rearranging I-*h* in *tert*-butyl alcohol-potassium *tert*-butoxide at 75°. Analytical and preparative vapor phase chromatographic (v.p.c.) procedures were developed for measuring the amounts of, and separating, I, II, and III. Control experiments established that 8–10% loss of I and II occurred during preparative v.p.c. separations, and that II and III were stable with respect to one another under the conditions of their formation. However, II tended to polymerize somewhat, and the amount of II recovered from the reaction was a much less accurate measure of the extent of reaction than was the amount of recovered starting material. Since the possibility existed that 2-phenyl-1-butene (IV) might serve as an intermediate in the production or interconversions of II and III, IV was submitted to the conditions of the isomerization reaction of I, and was found to be stable. In the isomerization of I, the ratio of II to III (*cis*- to *trans*-olefin) produced was approximately 50 to 1. The second-order rate constant for the isomerization of I under the above conditions was measured, and found to be $1.1 \times 10^{-4} \pm 0.1$ l. mole⁻¹ sec.⁻¹ at $75.0 \pm 0.1^\circ$. The progress of the reaction was followed by determining the % of I present in the distillable hydrocarbon fraction isolated from the reaction. In this connection, *o*-bromotoluene was used as an internal standard. The rate constant obtained was calculated neglecting loss of I during the analytical procedure, and is based on the calculated amount of I consumed by all processes. Table VI of the Experimental summarizes the data.

(5) D. J. Cram, *J. Am. Chem. Soc.*, **74**, 2137 (1952).

(6) D. J. Cram and M. R. V. Sahyun, *ibid.*, **85**, 1257 (1963).

Table I summarizes the results of the isomerization reactions of (+)-I-*h* carried out in deuterated media, and (+)-I-*d* in protonated media. The lowest concentration of isotopic pool in the medium was about 3 *M* (run 14, carried out in dimethyl sulfoxide-methanol), and most of the experiments were made in hydroxylic solvents or their deuterated counterparts. The least acidic solvent was triethylcarbinol, which probably has a pK_a of about 20. The pK_a of I is probably in the middle thirties. Temperatures for reaction ranged from 25° (run 14 in dimethyl sulfoxide-methanol) to 145° (runs 11–13) in ethylene glycol. The hydrocarbons isolated from the reactions were submitted to preparative v.p.c. separations into I and *cis*-olefin II in all runs except 4 (I-*h* in 1,2-dimethoxyethane, 4.9 *M* in *tert*-butyl alcohol-*O-d*) and 12 (I-*h* in ethylene glycol-*O-d*), which were carried out on a large enough scale also to allow separation of *trans*-olefin III. The estimated % reaction was based on the actual weight of I recovered, corrected for the estimated 8% loss during isolation. This correction is probably somewhat low in those reactions which were carried past 50%, since % losses during isolation probably increased as the absolute amount of the component decreased. This estimated % reaction was used to calculate estimated single-point second-order rate constants which were corrected to 25° with use of an assumed $\Delta H^* = 24$ kcal./mole. These final estimated rate constants are listed in Table I.

The rotations of starting material and the recovered starting material were measured and found to be identical within experimental error ($\pm 0.02^\circ$) in all runs except run 12. Particularly in run 4, which was carried through 4.5 half-lives, the rotations were measured with great care and were found to be identical. The large observed reading involved (-3.57°) allowed any racemization which might have occurred to be measured with better than 1% accuracy. Similar care was exercised in run 16 conducted in dimethyl sulfoxide, in which the isomerization of I-*h* was carried through 3.5 half-lives, and again the rotations of starting material and recovered starting material were identical (observed reading, 3.19°). Equal care was taken in run 12, in which I-*h* was isomerized in ethylene glycol-*O-d* for 1.5 half-lives. In this medium, a $6 \pm 1\%$ loss of optical activity in the recovered starting material was found (observed rotations were 3.21° initially and 3.02° finally).

The amount of deuterium in starting material I-*d*, in solvent, and in recovered I and II was measured in all runs, and the amount of deuterium in III was measured for runs 4 and 12. Combustion and falling drop method was used, and the analyses were good to an estimated ± 0.003 atom of deuterium per molecule.⁷ In cases where the amount of deuterium was low, combustion was performed on nondeuterated samples at the same time as the unknowns, and the results were compared. Insufficient III was recovered from runs 4 and 12 for combustion analysis and, therefore, both II and III from these runs were submitted to mass spectrographic analysis.⁸ Combustion analysis of II from run 4 gave 0.502, whereas mass spectro-

(7) Analyses were performed by J. Nemeth, Urbana, Ill.

(8) The authors are much indebted to Professor K. Biemann at M.I.T. for carrying out these determinations on samples from run 4, and to Dr. K. C. Dewhirst for those from run 12.

TABLE I
 RESULTS OF BASE-CATALYZED REARRANGEMENT OF 3-PHENYL-1-BUTENE (I) TO *cis*-2-PHENYL-2-BUTENE (II)

Run	Na- ture	Substrate		Solvent	Base		T, °C.	Time, min.	% recov.		Recov. I $\alpha_{\text{obsd}}^{25^\circ}$	No. atoms D ^e		Est. % reac. ^f	Est. k_2 ^g l. mole ⁻¹ sec. ⁻¹
		$\alpha_{\text{obsd}}^{25^\circ}$	Concn., M		Nature	Concn., M			I	II		I	II		
1	I- <i>h</i>	3.31 ^{ob}	0.34	(C ₂ H ₅) ₃ COD ^h	(C ₂ H ₅) ₃ COK	0.54	50	120	14	48	1.65 ^{oc}	0.01	0.44	85	2.1 × 10 ⁻⁵
2	I- <i>d</i> ⁱ	4.10 ^{ob}	.40	(C ₂ H ₅) ₃ COH	(C ₂ H ₅) ₃ COK	.40	50	215	38	9	2.04 ^{oc}	.95	.14	58	7.1 × 10 ⁻⁶
3	I- <i>h</i>	3.31 ^{ob}	.40	(CH ₃ OCH ₂) ₂ ^j	(CH ₃) ₃ COK	.40	50	90	28	23	1.65 ^{oc}	.01	.45	69	2.3 × 10 ⁻⁵
4	I- <i>h</i>	-3.57 ^{oc}	.40	(CH ₃ OCH ₂) ₂ ^k	(CH ₃) ₃ COK	.40	50	168	5	76	-3.57 ^{oc}	.058	.502 ^l	95	3.1 × 10 ⁻⁵
5	I- <i>d</i> ⁱ	4.10 ^{ob}	.25	(CH ₃ OCH ₂) ₂ ^m	(CH ₃) ₃ COK	.40	50	720	21	24	2.05 ^{oc}	.99	.14	77	3.6 × 10 ⁻⁶
6	I- <i>h</i>	1.78 ^{oc}	.42	(CH ₃) ₃ COI ⁿ	(CH ₃) ₃ COK	.39	75	240	50	25	1.79 ^{oc}	.013	.49	46	2.7 × 10 ⁻⁷
7	I- <i>d</i> ⁱ	4.10 ^{ob}	.23	(CH ₃) ₃ COH	(CH ₃) ₃ COK	.40	75	1167	34	33	2.05 ^{oc}	.985	.185	63	8.8 × 10 ⁻⁸
8	I- <i>h</i>	3.31 ^{ob}	.32	(CH ₃) ₃ COI ^o	(CH ₃) ₄ NOD	.28	50	121	24	18	1.65 ^{oc}	.00	.185	74	2.8 × 10 ⁻⁶
9	I- <i>h</i>	3.31 ^{ob}	.36	(CH ₃) ₃ COI ^p	(CH ₃) ₄ NOD	.36	50	93	13	23	1.63 ^{oc}	.01	.372	86	4.1 × 10 ⁻⁵
10	I- <i>d</i> ⁱ	4.10 ^{ob}	.36	(CH ₃) ₃ COH	(CH ₃) ₄ NOH	.27	75	168	49	21	2.07 ^{oc}	.94	.05	47	5.9 × 10 ⁻⁷
11	I- <i>h</i>	1.78 ^{oc}	.16	(DOCH ₂) ₂ ^q	DOCH ₂ CH ₂ OK	.10	144	270	39	19	1.78 ^{oc}	.013	.67	57	4.3 × 10 ⁻⁶
12	I- <i>h</i>	3.21 ^{ob}	.16	(DOCH ₂) ₂ ^r	DOCH ₂ CH ₂ OK	.10	145	690	33	43	3.02 ^{ob}	.042	.68 ^s	64	1.8 × 10 ⁻⁹
13	I- <i>d</i> ⁱ	4.10 ^{ob}	.18	(HOCH ₂) ₂	HOCH ₂ CH ₂ OK	.10	145	1260	36	5	1.05 ^{od}	.88	.103	61	9.3 × 10 ⁻¹⁰
14	I- <i>d</i> ⁱ	4.10 ^{ob}	.15	(HOCH ₂) ₂	HOCH ₂ CH ₂ OK	.10	145	800	52	8	2.05 ^{oc}	.885	.10	43	8.8 × 10 ⁻¹⁰
15	I- <i>d</i> ⁱ	4.10 ^{ob}	.40	(CH ₃) ₂ SO ^t	CH ₃ OK	.33	25	720	43	17	2.06 ^{oc}	.95	.26	52	5.1 × 10 ⁻⁶
16	I- <i>h</i>	3.19 ^{ob}	.40	(CH ₃) ₂ SO ^t	CH ₃ OK	.33	25	750	10	73	3.19 ^{ob}	89	1.5 × 10 ⁻⁴

^a Neat, $\lambda = 546 \mu$. ^b $l = 1$ dm. ^c $l = 0.5$ dm. ^d $l = 0.25$ dm. ^e Combustion and falling drop method, estimated error ± 0.003 atom per molecule. ^f Based on I recovered assuming 8% lost during recovery. ^g One-point second-order rate constant, % of reaction based on 100% - (% I recovered)/0.92. Rate constants then corrected to 25° assuming $\Delta H^* = 24$ kcal./mole. When I-*d* was used, the rate was not corrected for 12% I-*h* present. ^h 0.988 atom per molecule of deuterium. ⁱ 0.88 atom of deuterium in 3-position. ^j 4.9 M in (CH₃)₃COD (0.976 atom per molecule of deuterium). ^k 4.9 M in (CH₃)₃COD (0.997 atom per molecule of deuterium). ^l 0.495 atom per molecule of deuterium by mass spectrometer analysis (ref. 8). This value reflects loss of about 5% protium in the *cis*-2-phenyl-2-butene once formed, since this exchange occurs about 1% per half-life, and the reaction went about 5 half-lives. Had the 0.502 value been corrected for such exchange, the results of runs 3 and 4 would have been comparable. ^m 4.9 M in (CH₃)₃COH. ⁿ 0.976 atom per molecule of deuterium. ^o 0.59 atom of deuterium. ^p 0.82 atom per molecule of deuterium. ^q 1.98 atoms per molecule of deuterium. ^r 2.00 atoms per molecule of deuterium. ^s Mass spectral analysis of II gave 0.69 atom of deuterium per molecule, and for III gave 0.67 atom of deuterium per molecule. ^t 9% CH₃OH by weight.

 TABLE II
 HYDROGEN-DEUTERIUM EXCHANGE OF *cis*-2-PHENYL-2-BUTENE (II) AND *trans*-2-PHENYL-2-BUTENE (III)

Run	Na- ture	Substrate		Solvent	Base		T, °C.	Time, min.	% recov.	No. atoms D incorp. ^a	Est. k_2 l. mole ⁻¹ sec. ⁻¹ ^b
		Concn., M	Nature		Concn., M	Nature					
17	II	0.4	(C ₂ H ₅) ₃ COD ^c	(C ₂ H ₅) ₃ COK	0.40	50	120	69	0.009	1 × 10 ⁻⁷	
18	II	.4	(CH ₃ OCH ₂) ₂ ^d	(CH ₃) ₃ COK	.40	50	100	43	.013	2 × 10 ⁻⁷	
19	II	.4	(CH ₃) ₃ COD ^e	(CH ₃) ₃ COK	.47	75	240	85	.023	8 × 10 ⁻⁹	
20	II	.2	(DOCH ₂) ₂ ^f	DOCH ₂ CH ₂ OK	.10	145	300	38	.000	<8 × 10 ⁻¹²	
21	III	.4	(CH ₃ OCH ₂) ₂ ^d	(CH ₃) ₃ COK	.40	50	168	84	.002	2 × 10 ⁻⁶	

^a Combustion and falling drop method; estimated error ± 0.003 atom of deuterium per molecule. ^b One-point second-order rate constant for hydrogen-deuterium exchange corrected to 25° assuming $\Delta H^* = 24$ kcal./mole. ^c 0.988 atom of deuterium per molecule. ^d 4.9 M in (CH₃)₃COD (0.997 atom of deuterium per molecule). ^e 0.976 atom of deuterium per molecule. ^f 1.98 atoms of deuterium per molecule.

graphic analysis gave 0.495 atom of deuterium per molecule. The amount of isotopic exchange of (+)-I-*h* that occurred during all the runs but 4 and 12 was never more than 1.3%.

In run 4, where isomerization was carried 4.5 half-lives, the recovered starting material was 5.8% deuterated. This datum, coupled with the fact that racemization was $0 \pm 0.6\%$, allows limits to be set on the value of the ratio of k_e (rate constant for exchange) to k_a (rate constant for racemization). The value was calculated^{2c} to be >10 . Clearly, exchange at the benzyl position of 3-phenyl-1-butene (I) occurred in deuterated *tert*-butyl alcohol-potassium *tert*-butoxide with high retention of configuration. The data also allow the relative rates of deuterium introduction into the benzyl and terminal position to be estimated in run 4. Carbanion collapse with exchange occurs about 130 times as fast at the terminal as at the benzyl position in run 4. The same order of magnitude was observed for the runs carried out in the other solvent-base systems.

In run 12 (I-*h* in ethylene glycol-O-*d*) where isomerization was carried 1.5 half-lives, the recovered starting material was 4.2% deuterated. Thus, in this medium, $k_e/k_a \sim 0.7$, or substitution of I occurred at the benzyl position with substantial inversion of configuration.

Run 8 was made with (+)-I-*h* in *tert*-butyl alcohol-O-*d* to which was added tetramethylammonium hydroxide. Recovery and deuterium analysis of the *tert*-butyl alcohol at the end of the run indicated the solvent had dropped from 0.976 atom of deuterium per molecule to 0.590 atom of deuterium per molecule. Apparently the residual water of the added base and the possible exchange of the twelve protons of the tetramethylammonium hydroxide diluted the deuterium reservoir with a protium reservoir enough to destroy the validity of the experiment. An attempt was made to eliminate the difficulty in run 9 by using tetramethylammonium hydroxide which had been pre-treated with deuterium oxide. The *tert*-butyl alcohol recovered from run 9 contained 0.82 atom of deuterium per molecule. The protium diluent apparently came from partial exchange of the twelve hydrogens of the base. The tetramethylammonium residue was recovered as its chloride salt, and deuterium analysis⁷ of this salt indicated the presence of 5.7 atoms of deuterium per molecule.

Table II records the conditions and results of attempts to exchange the hydrogens of *cis*-olefin (runs 17-20) and *trans*-olefin (run 21) under conditions which approximated those of their formation in the runs of Table I. The largest amount of exchange observed

was 2.3% of one atom. Gross estimates of the second-order rate constants for these exchange reactions corrected to 25° (ΔH^* was assumed equal to 24 kcal./mole) are incorporated in Table II.

To establish that none of the deuterium was introduced into the phenylethenyl portion of *cis*-2-phenyl-2-butene (II) during runs 1, 3, 4, 6, 8, 9, and 11, the material (II) left over from analysis was combined and submitted to ozonolysis. The ozonide was reduced with lithium aluminum hydride, and the 1-phenylethanol formed was converted to 1-phenylethyl chloride, which was analyzed for deuterium and found to be free of the isotope. Appropriate control reactions (see Experimental) established that had deuterium been present in 1-phenylethanol, it would have persisted when converted to 1-phenylethyl chloride.

In Table III are found the % intramolecularities observed in isomerization reactions of I to II in 14 of the runs of Table I. In runs 1, 3, 4, 6, and 11, which involved I-*h* as substrate, the deuterium pool in the medium was large enough so that as the reaction proceeded the amount of protium produced by exchange

TABLE III
INTRAMOLECULARITY IN BASE-CATALYZED REARRANGEMENT OF 3-PHENYL-1-BUTENE (I) TO *cis*-2-PHENYL-2-BUTENE (III)

Run ^a	Substrate	Solvent ^b	% intra-mol.	% intra-mol. / % inter-mol.
1	I- <i>h</i>	(C ₂ H ₅) ₃ COD	56	1.3
2	I- <i>d</i>	(C ₂ H ₅) ₃ COH	17	0.2
3	I- <i>h</i>	(CH ₃ OCH ₂) ₂ -4.9 M (CH ₃) ₃ COD	55	1.2
4	I- <i>h</i>	(CH ₃ OCH ₂) ₂ -4.9 M (CH ₃) ₃ COD	50 ^d	1.0
5	I- <i>d</i>	(CH ₃ OCH ₂) ₂ -4.9 M (CH ₃) ₃ COH	17	0.2
6	I- <i>h</i>	(CH ₃) ₃ COD	51	1.0
7	I- <i>d</i>	(CH ₃) ₃ COH	23	0.3
8	I- <i>h</i>	(CH ₃) ₃ COD-(CH ₃) ₄ NOD	69 ^e	0.8 ^f
9	I- <i>h</i>	(CH ₃) ₃ COD-(CH ₃) ₄ NOD	55 ^e	
10	I- <i>d</i>	(CH ₃) ₃ COH-(CH ₃) ₄ NOH	6	0.06
11	I- <i>h</i>	DOCH ₂ CH ₂ OD	33	0.50
12	I- <i>h</i>	DOCH ₂ CH ₂ OD	31 ^g	0.45
13	I- <i>d</i>	HOCH ₂ CH ₂ OH	12	0.14
14	I- <i>d</i>	HOCH ₂ CH ₂ OH	11	0.13
15	I- <i>d</i>	91% (CH ₃) ₂ SO-9% CH ₃ OH	32	0.50

^a See Table I for conditions. ^b Base used was the potassium alkoxide except in runs 8, 9, and 10, where quaternary ammonium bases were employed. ^c In terms of Chart I, this ratio equals $k_2/(k_3 + k_4)$ values (see Discussion). ^d *trans*-2-Phenylbutene was produced 49% intramolecularly. ^e Extrapolated to 100% deuterated solvent and base, 45 ± 5% intramolecularity. ^f Based on 45% intramolecularity. ^g *trans*-2-Phenyl-2-butene was produced 33% intramolecularly.

was trivial and could be disregarded. The amount of deuterium introduced into II after it was formed was also trivial. In these runs, the % intramolecularity was calculated through use of simple expression 1. In runs 8 and 9, the solvent was only 59 and 82%

$$\% \text{ intramolecularity} = 100 - \% \text{ D in II} \quad (1)$$

deuterated at the end of the runs, respectively. In calculating the % intramolecularity for these runs, the assumption was made that no kinetic isotope effect for the proton or deuterium capture reaction by the intermediate carbanion was operative, and that, in effect, the concentration of deuterium donors in the solvent was constant and was the same as that found at the

end of the run. Equation 2 was employed, and provides only an estimate of the true value, particularly

$$\% \text{ intramolecularity} = 100 - 100 \left(\frac{\% \text{ D in II}}{\% \text{ D in solvent at end of run}} \right) \quad (2)$$

for run 8. The fact that the calculated values for intramolecularity in runs 8 and 9 do not agree (69 and 55%, respectively) indicates that the assumption is invalid. Extrapolation of the trend in values suggests that completely deuterated solvent would have provided a value of 45 ± 5% intramolecularity for runs of I-*h* in *tert*-butyl alcohol-*O-d* with tetramethylammonium hydroxide completely deuterated as base. This value will be assumed in later discussions.

Use of incompletely deuterated I-*d* (0.88 atom of deuterium per molecule) for runs 2, 5, 7, 10, 13, 14, and 15 introduces a complication in calculation of the % intramolecularity, particularly since the reactions were interrupted before all the starting material was consumed. Deuterium analysis of the 3-phenyl-1-butene recovered from these runs gave values in most cases higher than the 0.88 atom of deuterium per molecule at the beginning of the run. In such cases, it is clear that I-*h* isomerized faster than I-*d*. Account of this fact is taken in the use of eq. 3 for calculation of the

$$\% \text{ intramolecularity} = \frac{100 \times \text{fraction I reacted} \times \% \text{ D in II}}{(\% \text{ D in I initially} + \% \text{ D in I finally}) (\text{fraction I reacted} - 1)} \quad (3)$$

% intramolecularity for runs 2, 5, 7, 10, and 13-15, in which starting material contained 0.88 atom of deuterium per molecule.

Isotope effects for the isomerization reaction were calculated two ways (see Table IV for results). In the first, k_H/k_D was calculated from the estimated rate constants for reaction of I-*h* in deuterated solvent compared to reaction of I-*d* in protonated solvent (see Table I). In the second, k_H/k_D was calculated for the relative rates of isomerization of I-*h* and I-*d* in protonated solvent. These relative rates were calculated for runs 2, 5, 7, 13, and 15 from the initial and final amounts of deuterium in I, and from the % reaction. Equation 4 was used for this purpose.

$$\frac{k_H}{k_D} = \frac{[\log (1 - D \text{ in I initially}) / ((1 - D \text{ in I finally})(1 - \text{fraction I reacted}))]}{[\log (D \text{ in I initially}) / ((D \text{ in I finally})(1 - \text{fraction I reacted}))]} \quad (4)$$

Discussion

In the following sections, these subjects will be discussed in turn: (1) models for the mechanism of the base-catalyzed 1,3-proton transfer reaction; (2) stereochemical course of the base-catalyzed isotopic exchange reaction at the benzyl position of 3-phenyl-1-butene (I); (3) relative rates of proton removal and capture at the two sites of the allylic system; (4) isotope effects.

TABLE IV
ESTIMATED ISOTOPE EFFECTS FOR BASE-CATALYZED ISOMERIZATION 3-PHENYL-1-BUTENE (I) TO *cis*-2-PHENYL-2-BUTENE (II)

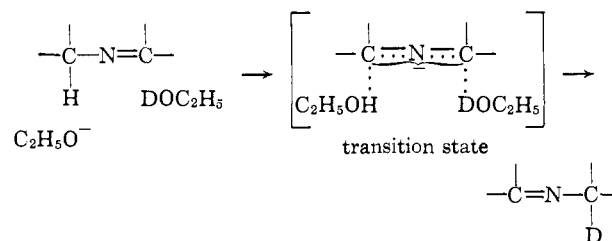
Run	Substrate	Solvent	T, °C.	k_H^{OH}/k_D^{OH}	k_H^{OD}/k_D^{OD}
2	12% ^c -I-h, 88% ^c -I-d	(C ₂ H ₅) ₃ COH	50	2	..
1	I-h	(C ₂ H ₅) ₃ COD	50	...	3
2	12% ^c -I-h, 88% ^c -I-d	(C ₂ H ₅) ₃ COH	50	...	3
5	12% ^c -I-h, 88% ^c -I-d	(CH ₃ OCH ₂) ₂ -4.9 M (CH ₃) ₃ COH	50	3	..
3	I-h	(CH ₃ OCH ₂) ₂ -4.9 M (CH ₃) ₃ COD	50	...	6
5	12% ^c -I-h, 88% ^c -I-d	(CH ₃ OCH ₂) ₂ -4.9 M (CH ₃) ₃ COH	50	...	6
7	12% ^c -I-h, 88% ^c -I-d	(CH ₃) ₃ COH	75	3.5	..
6	I-h	(CH ₃) ₃ COD	75	...	3
7	12% ^c -I-h, 88% ^c -I-d	(CH ₃) ₃ COH	75	...	3
13	12% ^c -I-h, 88% ^c -I-d	HOCH ₂ CH ₂ OH	145	1	..
14	12% ^c -I-h, 88% ^c -I-d	HOCH ₂ CH ₂ OH	145	1	..
11	I-h	DOCH ₂ CH ₂ OD	145	...	5
13	12% ^c -I-h, 88% ^c -I-d	HOCH ₂ CH ₂ OH	145	...	5
15	12% ^c -I-h, 88% ^c -I-d	98% (CH ₃) ₂ SO-9% CH ₃ OH	25	2.4	..

Models for the Mechanism of the Base-Catalyzed 1,3-Proton Transfer Reaction.—With all solvents, bases, temperatures, and locations of isotope labels (substrate or medium), the rearrangement of unconjugated olefin I to *cis*-olefin II occurred by a mixture of intramolecular and intermolecular paths. The existence of the intramolecular component in the reaction, which in some cases accounted for over half of the product, is incompatible with a one-stage mechanism in which a carbon-hydrogen (deuterium) bond is broken and the new deuterium (hydrogen) bond is made in the same transition state. Such a mechanism is only compatible with the intermolecular component of the reaction.

One-Stage Mechanisms.—Conceivably this one-stage mechanism could coexist with a second mechanism

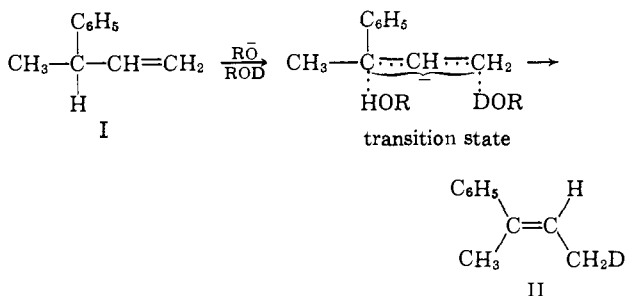
by Wilson, Ossorio, and Ingold⁹ as applied to the base-catalyzed isomerization of imines.

One-stage mechanism for base-catalyzed isomerization of imines

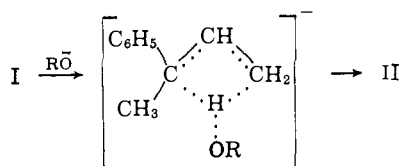


Of the possible multistage mechanisms, one can be envisioned in which a planar allylic carbanion is formed which is hydrogen bonded at its front face (side from which hydrogen or deuterium left the benzyl carbon) by the leaving group, and is hydrogen bonded at its back face by a molecule from the medium of the opposite isotopic type. Capture of hydrogen (or deuterium) at the front would give intramolecular isomerization, and capture of deuterium (or hydrogen) from the back would give intermolecular isomerization. The same intermediate should be formed irrespective of whether deuterated substrate was run in proton-donating media, or whether nondeuterated substrate was isomerized in deuterated media. Although such an intermediate would be generated in deuterated solvent in one case and protonated solvent in the other, aside from the specific solvation effects which are already taken into account in drawing such an intermediate, the differences in the general medium effects of deuterated and nondeuterated solvents should be negligible. Therefore, the ratio of hydrogen to deuterium in the 4-position of *cis*-2-phenyl-2-butene should be the same, irrespective of whether the solvent or substrate was labeled. The facts are in conflict with this requirement (see Table I). For example, in run 1 with I-h in deuterated triethylcarbinol, 0.44 atom of deuterium was in the product. In run 2 with I-d in ordinary triethylcarbinol, 0.17 atom of deuterium (corrected value) was in the product. In run 11 with I-h in deuterated ethylene glycol, 0.67 atom of deuterium was in the product, whereas in run 13 with I-d in ethylene glycol, only 0.10 atom of deuterium was in the product. All other pairs of runs provide a simi-

Intermolecular



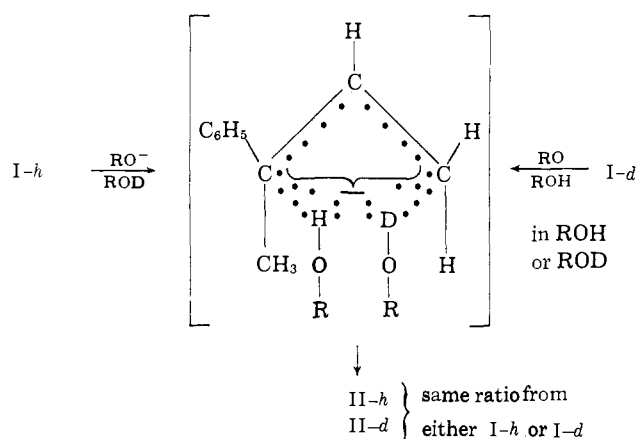
Intramolecular



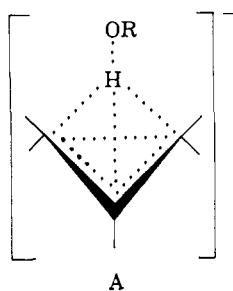
which was intramolecular in character. Both of these mechanisms would also have to be in competition with simple isotopic exchange at the benzyl carbon of I. The absolute rates of the isomerization reaction varied over many powers of 10 as solvent and base were changed. Furthermore, the ratio of rates of the intramolecular and of the intermolecular isomerization and of the simple exchange reaction *changed relatively little* with medium and base. Clearly, one-stage and two-stage mechanisms should respond differently to medium effects and, equally clearly, the simple exchange reaction is not one stage.² Thus, it is highly improbable that a one-stage intermolecular mechanism is operative. This conclusion conflicts with that drawn

(9) For summary see C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p. 574.

lar picture. This mechanism is incompatible with the facts.



In contrast to the above mechanisms, that outlined in Chart I is in harmony with all the facts. In this scheme, base as an ion-pair (in nondissociating solvents) or as a free anion (in dissociating solvents) abstracts



a proton from the benzyl carbon atom to form in one transition state a carbanion hydrogen bonded at both the benzyl and the methylene carbon at the same time. This discrete intermediate possesses a geometry in which the three carbon atoms of the allylic anion are in one plane and the molecule of alcohol formed by proton abstraction is above the plane of the allylic anion. The hydrogen of this alcohol molecule is hydrogen bonded to the terminal carbon atoms of the allylic system. These terminal carbon atoms might form a better hydrogen bridge if the hybridization is not pure sp^2 , but is something like $sp^{2.3}$. Possibly the allylic carbanion has some three-membered ring character, which would place some negative charge on the central carbon of the allylic anion, and bring all four atoms (three carbon atoms and one hydrogen) closer together. In the extreme, the bridged anion would resemble a trigonal bipyramid, with the three carbon atoms of the allylic system as the base and the hydrogen at the apex (A). Such a formulation would allow negative charge to be distributed on all three carbon atoms, and even on oxygen. No evidence requires such a species as A.

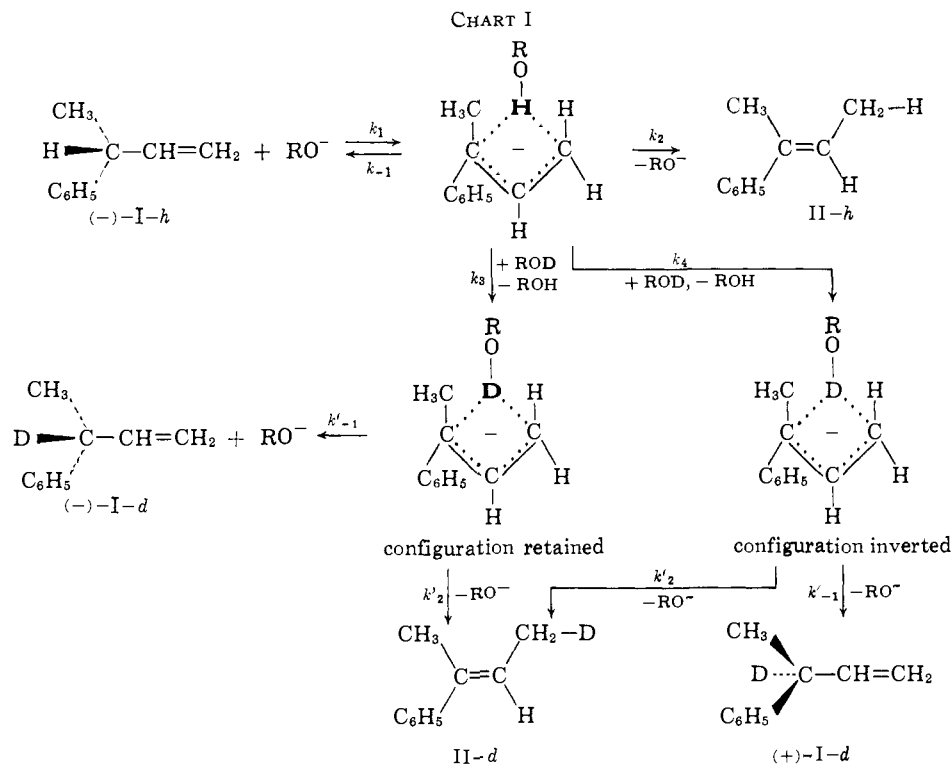
The hydrogen-bonded anion (whatever its exact geometry) could collapse to starting material with a rate constant, k_{-1} , or collapse to intramolecularly rearranged material II-h (rate constant k_2), or undergo exchange of ROH with ROD molecules of the medium to give a new isotopically labeled anion. If this last process occurred by exchange at the front (rate constant k_3), the new anion would have the same configuration as the original anion. If it occurred by ex-

change at the back (rate constant k_4), the new anion would be enantiomeric to the original anion. This new anion (irrespective of configuration) could then collapse to isotopically labeled unconjugated olefin I-d (rate constant k'_{-1}), or to isotopically labeled conjugated olefin II-d (rate constant k'_2). In this scheme, the cation has been omitted, although in solvents such as triethylcarbinol, *tert*-butyl alcohol, or dimethoxyethane an ion-pair should replace the free anion. Certainly, the intramolecular proton transfer does not require the presence of a cation. Otherwise no intramolecularity would have been observed in ethylene glycol or dimethyl sulfoxide-methanol.

The striking feature about the data of Table III is that the % intramolecularity varies so little with the solvent and base composition. In terms of the ratio of rate constants for collapse to exchange of the initially formed anion (Chart I), $k_2/(k_3 + k_4)$ varies only from 1.2 (run 1) to 0.06 (run 10) or by a factor of only 20. Simply by changing the position of the isotopic label (substrate *vs.* solvent), the $k_2/(k_3 + k_4)$ values changed by factors that ranged from about 4 to 14. This isotope effect will be discussed in a later section. Comparison of those runs in which I-h served as substrate and potassium alkoxides as bases, intramolecularity values are found which range between 56 for run 1 (triethylcarbinol-O-d) and 31 for run 12 (ethylene glycol-O-d). Comparison of those runs in which I-d was substrate and potassium alkoxides were bases gives % intramolecularity values which range between a high of 32 for run 15 (dimethyl sulfoxide-methanol) to a low of 11 for run 14 (ethylene glycol). Thus $k_2/(k_3 + k_4)$ values changed by factors of less than 4 as solvent was changed from triethylcarbinol (nondissociating, $pK_a \sim 20$) to ethylene glycol (dissociating, $pK_a \sim 14$) to dimethyl sulfoxide-methanol (dissociating, $pK_a \sim 16$ for methanol, but proton donors diluted and hydrogen bonded). A larger variation of $k_2/(k_3 + k_4)$ value (~ 5) was observed when I-d was run in *tert*-butyl alcohol and the base was changed from potassium *tert*-butoxide to tetramethylammonium hydroxide (runs 6, 8, and 9).

No correlation is visible between the intramolecularity and such factors as solvent acidity, concentration of proton donors (changes were very small), dissociating power of solvent, or the character of the base. Features such as the existence of the allylic anion as part of an ion-pair or in a dissociated state or coordination of the cation of the ion-pair with solvent seem to play roles subservient even to the isotope effects. These results contrast with those observed for the stereochemistry of the base-catalyzed hydrogen-deuterium exchange reaction at asymmetric carbon.² The steric course of the exchange reaction was little affected by the placement of the isotope (substrate or solvent), and greatly affected by the other factors. Unlike the stereochemical paths, the intramolecular reaction course seems dependent largely on hydrogen bonding.

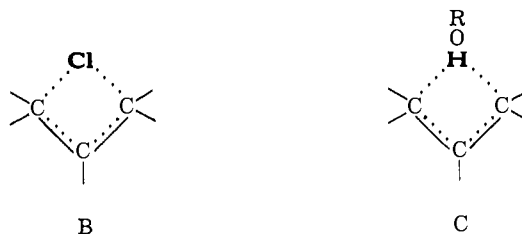
Schriesheim, *et al.*,^{4a} observed that perdeuterio-1-pentene isomerized to perdeuterio-2-pentene at 55° in dimethyl sulfoxide 0.43 M in potassium *tert*-butoxide and 0.43 M in *tert*-butyl alcohol. The rate of isomerization was about 16 times that of exchange. The higher intramolecularity observed here than in our



system may be attributed either to the fact that the acidity of 1-pentene is much less than that of 3-phenyl-1-butene, or to the much smaller isotopic pool used in the pentene experiment. The former explanation seems more probable, since Doering, *et al.*,^{4b} found that intramolecular base-catalyzed rearrangement of 7,7-dideuteriocycloheptatriene in triethylcarbinol was 12 times the isotopic exchange rate. The relative values of k_2 (proton capture rate constant) and k_3 or k_4 (exchange of alcohol molecules hydrogen bonded to anion) should change with changes in the $\text{p}K_a$'s of the hydrocarbon and the proton pool in the medium. The greater the difference in $\text{p}K_a$ of the two acids involved in the isotopic exchange reaction, the greater should be the value of $k_2/(k_3 + k_4)$, and the greater should be the intramolecularity.

Interestingly, the base-catalyzed rearrangement of 7,7-dideuteriocycloheptatriene in dimethyl sulfoxide-triethylcarbinol-potassium triethylcarboxide occurred with little intramolecularity.^{4b} Unlike the simple allylic systems, the cycloheptatrienide anion has seven hydrogen-bonding sites, and one alcohol molecule could at most hydrogen bond to only two or three of them at one time. Possibly, intramolecularity in this system is dependent on an ion-pair being the principal intermediate. The potassium ion could be close to three adjacent charge-distributing sites at the most, thus localizing negative charge on these sites. In such an intermediate, proton capture could occur only at these sites, since charge separation in a solvent of low dielectric constant would result should proton capture occur at a distant site. In triethylcarbinol (low dielectric constant), an ion-pair is expected to be the intermediate, and intramolecularity is observed.^{4b} In dimethyl sulfoxide (high dielectric constant), a carbanion is expected to be the intermediate,^{2a} protonation at all seven hydrogen bonding sites becomes possible, and intermolecularity is observed.^{4b}

The observed competition between intramolecular and intermolecular allylic 1,3-proton transfers of carbanion chemistry recalls the similar phenomena found in allylic 1,3-chloride ion transfers of carbonium ion chemistry.¹⁰ Thus, during the acetolysis of α,α -dimethylallyl chloride, intramolecular isomerization to γ,γ -dimethylallyl chloride occurred at rates of the same order of magnitude as the solvolyses rates. A bridged allylic chloride was formulated (B) whose geometry resembles that of the bridged protium allylic carbanide of the present investigation (C).

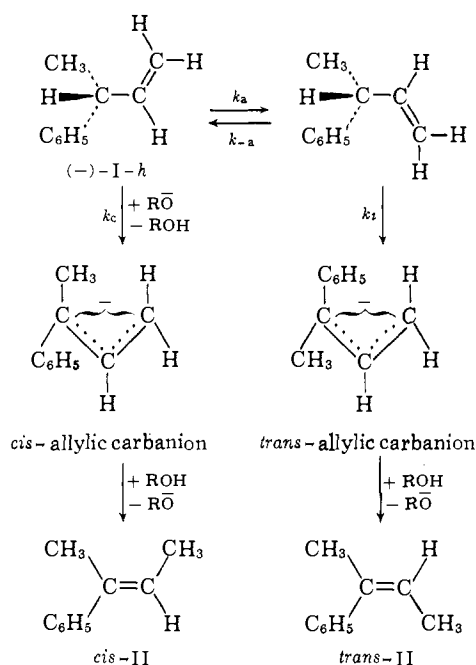


In the kinetic runs carried out on I-h in *tert*-butyl alcohol-potassium *tert*-butoxide (see Table VI of Experimental), the ratio of *cis*- to *trans*-olefin produced in the isomerization was about 60. The explanation is formulated in Chart II. Evidence has been gathered elsewhere that proton capture by phenylallylic anions occurs faster than *cis-trans* isomerization of such anions.¹¹ Thus, the ratio of *cis*- to *trans*-2-phenyl-2-butene produced is governed by the relative rates of proton abstraction from I to give the *cis* and the *trans* allylic anions. The rate constants for generation of these anions (k_c and k_t) are undoubtedly many orders of magnitude lower than those for conformational equilibration of the starting material (k_a and k_{-a}) and, therefore, $k_c/k_t = \text{cis/trans}$ produced. The

(10) W. G. Young, S. Winstein, and H. L. Goering, *J. Am. Chem. Soc.*, **73**, 1958 (1951).

(11) D. J. Cram and D. H. Hunter, *ibid.*, **86**, 5478 (1964).

CHART II



transition state leading to *trans* allylic anion must be of higher energy because charge must be much more localized than in that leading to *cis*, owing to the greater steric inhibition of coplanarity of the conjugated system in the *trans* as compared to the *cis* allylic anion.

It is interesting to compare the ratio of *cis*- to *trans*-2-phenyl-2-butenes produced by this base-catalyzed rearrangement to that obtained during the solvolytic elimination of 2-phenyl-2-butyl chloride in acetic acid.^{5b} In the latter carbonium ion reaction, the ratio of *cis*- to *trans*-olefin produced was about 11. Both of these values (60 and 11) are greater than the *cis/trans* value at equilibrium (4.2).^{5b} The higher values obtained in the kinetically controlled processes involving carbanions and carbonium ions undoubtedly reflect the greater importance of delocalization of charge in a transition state than the delocalization of electrons leading to charge separation in a ground state.

In run 4 (dimethoxyethane-*tert*-butyl alcohol-*O-d*-potassium *tert*-butoxide) and run 12 (ethylene glycol-*O-d*-potassium ethylene glycoxide), both *cis*- and *trans*-2-phenyl-2-butene were produced with the same amount of intramolecularity ($50 \pm 1\%$ in run 4, and $32 \pm 1\%$ in run 12). Apparently the values of $k_2/(k_3 + k_4)$ are little affected by whether a *cis* or *trans* allylic carbanion is involved, at least in this system. Since the alcohol molecule hydrogen bonded to the anion is either above or below the plane of the allylic anion and its attached groups, its behavior is not expected to be very sensitive to the exact steric situation in the plane of the allylic carbanion.

Stereochemical Course of Base-Catalyzed Isotopic Exchange Reaction at the Benzyl Position of 3-Phenyl-1-butene (I).—The mechanism of Chart I can be used to explain the observed retention of configuration for simple exchange of hydrogen for deuterium at benzyl carbon in run 4 (dimethoxyethane-*tert*-butyl alcohol-potassium *tert*-butoxide). The potassium ion of the first ion-pair has as its ligands the molecule of alcohol initially hydrogen bonded to the carbanion, as well as a

molecule of isotopically labeled alcohol from the medium. The potassium ion and its ligands are associated with only one of the two faces of the allylic anion and, therefore, the ion-pair is asymmetric. Rotation of the potassium ion with its ligands with respect to the anion provides an anion hydrogen bonded to a molecule from solvent (ROD), but which possesses the same configuration as the original species. Collapse of this new asymmetric ion pair to 3-phenyl-1-butene provides isotopically exchanged material of retained configuration ($k_e/k_a \gtrsim 10$). This mechanism resembles that used to explain values of k_e/k_a of 10 or more for base-catalyzed exchange and racemization for optically active 2-phenylbutane^{2a} and 2-(*N,N*-dimethylamido)-9-methylfluorene^{2c} in nondissociating solvents with potassium oxide bases as catalysts.

The mechanism of Chart I is equally compatible with the observed inversion of configuration for simple exchange of hydrogen for deuterium at benzyl carbon in run 12 (ethylene glycol-*O-d*-potassium ethylene glycoxide). In this dissociating solvent, the glycoxide anion is the base. In this first intermediate, the leaving group (H) is hydrogen bonded at the front face of the allylic carbanion. Proton capture at the benzyl position (k_{-1}) gives back starting material of unchanged configuration. Exchange of hydrogen-bonded ROH at the front side by ROD (from solvent) at the back side (k_1) gives an asymmetric carbanion of inverted configuration. Deuterium capture from the back side at the benzyl position (k'_{-1}) produces exchanged starting material of inverted configuration ($k_e/k_a \sim 0.7$). Operation of this mechanism is dependent on the ion-pair dissociating properties of the solvent. Back-side deuterium capture within an ion-pair would produce a "product separated ion-pair," and charge separation in a nondissociating solvent would be energetically unfavorable. This mechanistic scheme is similar but not identical with those employed to explain values of k_e/k_a between 0.5 and unity observed in glycol and methanol for the 2-phenylbutane,^{2a} 2-(*N,N*-dimethylamido)-9-methylfluorene,^{2c} and 2-phenylbutyronitrile^{2d} systems.

Relative Rates of Proton Capture and Removal at the Two Sites of the Allylic System.—In all media and with all bases, the rate of introduction of isotope into the terminal methyl group was about two powers of ten faster than into the benzyl position. In terms of the rate constants of Chart I, $k'_2/k'_{-1} \gg 1$. Since any isotope effect should be approximately the same for proton (deuteron) capture at the two sites of the ambident anion, $k'_2/k'_{-1} \sim k_2/k_{-1}$, and, therefore, $k_2 \gg k_{-1}$. Consequently, $(k_2 + k_3) \gg k_{-1}$. In other words, recovery by the benzyl carbon of the proton originally attached to that carbon is slow compared to the isomerization reaction. Since the equilibrium constant between I and II lies far on the side of II (conjugated olefin), the ambident anion reacts faster at the site which provides the more thermodynamically stable olefin. This fact is in conflict with the generalization put forth by Ingold, "when a proton is supplied by acids to the mesomeric anion of weakly ionizing tautomers of markedly unequal stability, then the tautomer which is the most quickly formed is the thermodynamically least stable; it is also the tautomer from which the proton is lost most quickly to bases."¹²

A test of the second part of the above generalization is found in the relative rates of proton abstraction from 3-phenyl-1-butene (I) and *cis*-2-phenyl-2-butene (II). Comparison of the crude rate constants for isomerization of I (Table I) and isotopic exchange of II (Table II) indicates that proton abstraction from the less stable isomer is 30 to 400 times faster than from the more stable isomer, depending on solvent. Thus, the facts are compatible with the second part of the Ingold generalization, since "the thermodynamically least stable . . . is the tautomer from which the proton is lost most quickly to bases."

Isotope Effects.—Table IV lists two different kinds of isotope effects. The set calculated from the competition experiments for isomerization of the mixture of 12% I-*h* and 88% I-*d* in nondeuterated solvents represents true kinetic isotope effects for proton abstraction from carbon, since the solvent was the same for each isotopically labeled substrate. The values of k_H^{ROH}/k_D^{ROH} ranged from a high of 3.5 (*tert*-butyl alcohol-potassium *tert*-butoxide at 75°) to a low of 1 (ethylene glycol-potassium ethylene glycolate at 145°). No correlation between the magnitude of the values of k_H^{ROH}/k_D^{ROH} and the pK_a or dissociating power of the solvent is visible in these results. The most dissociating solvent, 91% dimethyl sulfoxide-9% methanol, gave k_H/k_D of 2.4 (25°), whereas the least dissociating solvent, triethylcarbinol, gave $k_H/k_D = 2$ (50°). The most acidic solvent, ethylene glycol, gave $k_H/k_D = 1$ (145°), whereas the least acidic solvent, triethylcarbinol, gave $k_H/k_D = 2$ (50°).

The values listed are all on the low side for isotope effects for base-catalyzed proton abstraction reactions. Although the value of unity in ethylene glycol was obtained at a temperature (145°) which would tend to reduce the isotope effect somewhat, certainly the reduction would not be more than 40% over what would be obtained at 50 or 75°. No pre-equilibrium for the exchange reaction can be invoked since $(k_2 + k_3) \gg k_{-1}$ (see Chart I and previous section). Thus, a low isotope effect alone cannot be used as evidence for a pre-equilibrium in a base-catalyzed hydrogen-deuterium exchange reaction at carbon. On the other hand, negative isotope effects ($k_H^{ROH}/k_D^{ROH} \sim 0.3$ to 0.5) have been observed in some exchange and racemization reactions,^{2b} and the present results in no way vitiate the pre-equilibrium explanation in those cases.

A possible explanation for the low kinetic isotope effect (k_H/k_D) and its dependence on the solvent-base is that the transition state for proton or deuterium abstraction resembles the carbanion to an extent which depends on the activity of that anion. The maximum isotope effect is to be expected only if the transition state is symmetrical (hydrogen is equally bonded to oxygen and carbon).¹³ Such an explanation implies that the isotope effect should be highest for the strongest base, and least for the weakest base. If rate is used as a criterion of base activity, then isotope effects should decrease with the following base-medium changes: $CH_3OK-(CH_3)_2SO > (C_2H_5)_3COK-(C_2H_5)_3COH \sim (CH_3)_3COK-(CH_3OCH_2)_2 > (CH_3)_3COK-(CH_3)_3COH > HOCH_2CH_2OK-HOCH_2CH_2OH$. Observed isotope effects decreased in the order: $(CH_3)_3-$

$COK-(CH_3)_3COH > (CH_3)_3COK-(CH_3OCH_2)_2 > CH_3OK-(CH_3)_2SO > (C_2H_5)_3COK-(C_2H_5)_3COH > HOCH_2CH_2OK-HOCH_2CH_2OH$. The lack of correlation indicates the situation is too complex for simple interpretation.

Those values of k_H^{ROD}/k_D^{ROH} in Table I which were calculated from two different runs reflect both a kinetic and solvent-base isotope effect. The solvent-base isotope effect, k_H^{ROD}/k_H^{ROH} (protonated substrate), can be calculated by dividing k_H^{ROH}/k_D^{ROH} into k_H^{ROD}/k_D^{ROH} , and the resulting values are listed in Table V.

TABLE V

ESTIMATED SOLVENT ISOTOPE EFFECTS FOR BASE-CATALYZED ISOMERIZATION OF 3-PHENYL-1-BUTENE (I) TO *cis*-2-PHENYL-2-BUTENE (II)

Run	Solvent	k_H^{ROD}/k_H^{ROH}
1 + 2	Triethylcarbinol	1.5
3 + 5	Dimethoxyethane- <i>tert</i> -butyl alcohol	2
6 + 7	<i>tert</i> -Butyl alcohol	0.9
11 + 12	Ethylene glycol	5

In all media, $k_H^{ROD}/k_H^{ROH} \gtrsim 1$, reaching 5 in ethylene glycol and 0.9 in *tert*-butyl alcohol. The larger effect in ethylene glycol is attributed to the facts that dissociated anion is the active species, and its activity depends primarily on the energy of its hydrogen bonds to hydroxyl groups, both intra- and intermolecular. Apparently, ROD is poorer at hydrogen bonding than ROH and, as a result, $R\ddot{O} \dots DOR$ has a higher activity than $R\ddot{O} \dots HOR$.¹⁴ The factor of 5 in ethylene glycol is higher than any of the true kinetic isotope effects and is particularly striking because of the high temperature (145°). The other solvent isotope effects probably reflect both hydrogen bonding and cation solvation, and are very complex.

The isotope effects were the single most important factor in controlling the intramolecularity of the isomerization reaction. The values of the ratios, % intramolecular/% intermolecular, decreased by factors that ranged from about 4 to 13 when deuterium was shifted from solvent to substrate. In other words, intramolecular proton transfer occurred more readily than intermolecular deuterium transfer. In terms of the mechanism of Chart I, % intramolecular/% intermolecular = $k_2/(k_3 + k_4)$. The term $k_2/(k_3 + k_4)$ is the ratio of the rate constant for collapse of a hydrogen-bonded carbanion to the sum of the rate constants for exchange front and back of the solvent molecule hydrogen bonded to the carbanion with its isotopic counterpart in the medium. The value of k_2 for I-*h* should be greater than k_2 for I-*d*, since the O-H bond should be broken faster than the O-D bond. The value of $k_3 + k_4$ would be lower when $ROH \dots \bar{C}$ goes to $ROD \dots \bar{C}$ than in the reverse direction if ROD is a poorer hydrogen-bonding species than ROH. Thus, both a true kinetic isotope effect and a solvent isotope effect might combine to provide the large isotope effects observed for isomerization of I-*h* in ROD solvent as compared to I-*d* in ROH solvent (last column of Table IV).

(14) E. Whalley and M. Falk [*J. Chem. Phys.*, **34**, 1569 (1961)] have provisionally concluded that the hydrogen bond in methanol has about the same or a little greater strength than the deuterium bond in deuterated methanol. On the other hand, C. J. Creswell and A. L. Alred [*J. Am. Chem. Soc.*, **84**, 3966 (1962)] have concluded that in the system fluoroform-tetrahydrofuran-cyclohexane deuterium forms a stronger hydrogen bond than protium.

(12) C. K. Ingold, ref. 9, p. 565.

(13) F. H. Westheimer, *Chem. Rev.*, **61**, 265 (1961).

Particularly interesting is the result of substituting tetramethylammonium hydroxide for potassium *tert*-butoxide in *tert*-butyl alcohol on the isotope effect for intramolecularity ($\% \text{ intramol.} / \% \text{ intermol.}$) $_{1-h}^{\text{ROD}}$ / ($\% \text{ intramol.} / \% \text{ intermol.}$) $_{1-d}^{\text{ROH}}$. This change in base changed the value of the ratio from about 4 to 13. Probably the potassium ion of the ion-pair coordinated with the molecule of solvent hydrogen bonded to the carbanion and in so doing had an acidifying effect on that molecule. As a result, that hydrogen or deuterium was transferred somewhat faster to carbon (k_2 increased) when coordination was possible (potassium ion present) than when not (tetramethylammonium ion present).

Experimental

Preparation of Optically Active 3-Phenyl-1-butene (I), *cis*-2-Phenyl-2-butene (II), *trans*-2-Phenyl-2-butene (III), and 2-Phenyl-1-butene (IV).—These four alkenes were prepared as in previous investigations,^{5a,b} except for improvements in procedures noted below. The samples were purified by preparative vapor phase chromatography on a 6-ft. column packed with 23% 4-methyl-4-nitropimelonitrile on firebrick at a column temperature of 107°, with helium as carrier gas. The indexes of refraction obtained are: I, n_D^{25} 1.5052; II, n_D^{25} 1.5398; III, n_D^{25} 1.5191; IV, n_D^{25} 1.5262.

An improved procedure for the preparation of 3-phenyl-1-bromobutane, an intermediate in the synthesis of I,^{5a} is: Hydrogen bromide (dry gas) was passed through a solution of 32 g. of 3-phenyl-1-butanol in 16 g. of pyridine at room temperature. The initially formed precipitate of pyridinium hydrobromide partially dissolved as more hydrogen bromide was added. After the initial exothermic reaction subsided, the mixture was gently heated at 95° for 24 hr. as hydrogen bromide was continuously added. The resulting mixture was poured onto ice, and the oil extracted into ether. The organic solution was, in turn, washed with water, saturated sodium bicarbonate solution, and again with water. The solution was dried, evaporated, and the residual oil was distilled at 95° (4.5 mm.) to give 39.1 g. (90%) of 3-phenyl-1-bromobutane, n_D^{25} 1.5352. Analysis of this material by vapor phase chromatography and thin layer chromatography demonstrated purity.

Preparation of (+)-3-phenyl-1-butene ((+)-I) involved 3-phenyl-1-butyric acid, n_D^{25} 1.5144, α_D^{25} +24.94° ($l = 1 \text{ dm.}$, neat), which gave 3-phenyl-1-butanol, n_D^{25} 1.5177, α_D^{25} +16.82° ($l = 1 \text{ dm.}$, neat) which, in turn, gave 3-phenyl-1-bromobutane, n_D^{25} 1.5352, α_D^{25} +44.94° ($l = 1 \text{ dm.}$, neat), which was converted to 1-(*N,N*-dimethylamino)-3-phenylbutane, n_D^{25} 1.4932, α_D^{25} +10.00° ($l = 1 \text{ dm.}$, neat), which gave (+)-I, n_D^{25} 1.5052. This material was used in the isomerization reactions.

Preparation of (+)-3-Phenyl-1-butene-3-*d* ((+)-I-*d*).—Hydrotonitrile¹⁵ was carefully distilled through a 30-in. spinning band column, and the main fraction (b.p. 131° at 25.6 mm., n_D^{25} 1.5109) was found to be homogeneous to vapor phase chromatography on a di-2-ethylhexyl sebacate column at 150° with helium as carrier gas.

Deuterium was introduced into this nitrile as follows. A solution of 440 g. of nitrile in 500 ml. of pure benzene was mixed with a solution prepared by treating 0.1 g. of sodium with 60 g. of 99.5% deuterium oxide at 0° under nitrogen. The vigorously stirred mixture was held at reflux for 3 hr., the aqueous layer was separated, and a fresh 60 ml. of the original solution of sodium deuteride in deuterium oxide was added. The stirred mixture was again held at reflux temperature for 3 hr., and the layers again separated. This procedure was repeated until one atom of deuterium was introduced as determined by n.m.r., the benzene solution was washed with dilute hydrochloric acid and water, dried, and evaporated at 25 mm. The residual oil was distilled, b.p. 121–122° (23 mm.), n_D^{25} 1.5105, 0.994 atom of deuterium per molecule,⁷ wt. 353 g. (80%). The benzyl hydrogen of protium nitrile appeared in the n.m.r. spectrum as a quartet centered at 6.24 τ . This absorption was completely absent in the spectrum of the deuterated material. The methyl hydrogens of the protium nitrile were split into a doublet, but appeared as a singlet at 8.56 τ in the deuterated nitrile.

Deuterated nitrile was hydrolyzed to deuterated hydrotronic acid as follows. To 353 g. of the above nitrile was added a basic deuterium oxide solution prepared by adding 67 g. of sodium metal to 1 kg. of deuterium oxide (>99.5% D₂O) with vigorous stirring at 0° under an atmosphere of dry nitrogen. The two-phase mixture was held at reflux for 18 hr. with vigorous stirring, during which time the mixture became homogeneous. The mixture was cooled, and the deuterium oxide was evaporated under reduced pressure. To the remaining solid was added 2000 ml. of cold 2 *N* hydrochloric acid, and the oil that separated was extracted with pure pentane. The pentane solution was washed with water, and was extracted with two 1500-ml. portions of 2 *N* sodium hydroxide solution. The basic extracts were combined, washed with pentane, and acidified with cold 2 *N* hydrochloric acid. The oil was extracted with pentane, the pentane layer was dried, and the solvent was evaporated. The residual oil was distilled to give 377 g. (94%) of 2-deuterio-2-phenylpropionic acid, b.p. 100° (0.13 mm.), n_D^{25} 1.5212, 1.094 atoms of deuterium per molecule.⁷ A sample of this proved homogeneous to vapor phase chromatography on a di-2-ethylhexyl sebacate column held at 150° with helium as carrier gas. Hydrolysis of a nondeuterated sample of hydrotronitrile by the above procedure gave 2-phenylpropionic acid, b.p. 106° (0.5 mm.), n_D^{25} 1.5202. *Anal.* Calcd. for C₉H₁₀O₂: C, 71.98; H, 6.71. Found: C, 72.26; H, 6.99.

This material (377 g.) was homologated by the Arndt–Eistert synthesis in 15 separate batches to avoid use of large amounts of diazomethane at any one time. A typical run was as follows.

A mixture of 5.0 g. of deuterated 2-phenylpropionic acid and 8 g. of thionyl chloride was allowed to stand at 25° for 12 hr., and the excess reagent was removed at 30 mm. of pressure. The residue was distilled at 77° (4.5 mm.) to give 5.6 g. of 2-deuterio-2-phenylpropionyl chloride, which was dissolved in 30 ml. of ether. This solution was added dropwise over a period of 45 min. to an ice-cold solution of 4.2 g. of diazomethane¹⁶ in 125 ml. of ether.¹⁷ The reaction mixture was allowed to stand for 24 hr. at 25°, and the excess diazomethane and ether were evaporated at 25 mm. At this point, the oily diazoketone from this run was combined with that from the other 14 runs, and this material was dissolved in 1000 ml. of methanol. To this solution was added dropwise, over a period of 20 min. at 25°, a solution of 74 g. of silver benzoate in 240 g. of triethylamine. The mixture was stirred for 15 min., the solvent was evaporated at 25 mm., and the residue was washed with ether. The mixture was filtered, and the filtrate was washed with dilute acid, dilute base, and finally with water. The ether layer was dried, evaporated, and the residual oil was distilled, b.p. 65–66° (0.3 mm.), wt. 160 g. (36% yield of methyl 3-deuterio-3-phenylbutyrate). This material (179 g.) was hydrolyzed by refluxing with 600 ml. of 2 *N* potassium hydroxide for 0.5 hr. The reaction mixture was cooled, washed with ether, acidified with cold dilute hydrochloric acid, and the material that separated was extracted with ether. The ether solution was dried, evaporated, and the residual oil was distilled to give 165 g. (100%) of 3-deuterio-3-phenylbutanoic acid, b.p. 127° (1.2 mm.), n_D^{25} 1.5162, pure to vapor phase chromatography on silicone gum at 150° with helium as carrier gas. The benzyl hydrogen of protium acid appeared in the n.m.r. spectrum as a multiplet centered at 6.82 τ . This absorption was completely absent in the spectrum of the deuterated material. The methyl hydrogens of the protium acid were split into a doublet centered at 8.84 τ , but appeared as a singlet at 8.79 τ in the deuterated acid. The methylene hydrogens of the protium acid were split into a doublet centered at 7.55 τ , but appeared as a singlet at 7.51 τ in the deuterated acid. This material showed 0.88 atom of deuterium per molecule.⁷

The nondeuterated 3-phenylbutanoic acid prepared by the above procedure had n_D^{25} 1.5169. *Anal.* Calcd. for C₁₀H₁₂O₂: C, 73.14; H, 7.37. Found: C, 73.37; H, 7.51.

This acid was resolved according to the method of Rupe.¹⁸ Preparation of (+)-3-deuterio-3-phenyl-1-butene ((+)-I-*d*) involved 3-deuterio-3-phenylbutyric acid, n_D^{25} 1.5162, α_D^{25} +3.17° ($l = 1 \text{ dm.}$, neat), 0.88 atom of deuterium per molecule, which gave 3-deuterio-3-phenyl-1-butanol, α_D^{25} +22.4° ($l = 1 \text{ dm.}$, neat) which, in turn, gave 3-deuterio-3-phenyl-1-bromo-

(15) D. J. Cram and J. E. McCarty, *J. Am. Chem. Soc.*, **76**, 5741 (1954)

(16) F. Arndt, "Organic Syntheses," Coll. Vol. 11, John Wiley and Sons, Inc., New York, N. Y., 1943, p. 461.

(17) The amount of diazomethane was determined by the method of L. F. Fieser, "Experiments in Organic Chemistry," 3rd Ed., D. C. Heath and Co., Boston, Mass., 1957, p. 313.

(18) H. Rupe, *Ann.*, **369**, 323 (1909).

butane, n^{25D} 1.5350, which was converted to 1-(*N,N*-dimethylamino)-3-deuterio-3-phenylbutane, $\alpha^{25D} + 13.1^\circ$ ($l = 1$ dm., neat), which gave (+)-*I-d*, n^{25D} 1.5052, $\alpha^{25D} + 4.10^\circ$ ($l = 1$ dm., neat), 0.88 atom of deuterium per molecule.⁷ This material was used in the isomerization reaction.

Separation of the Phenylbutenes I, II, and III by Vapor Phase Chromatography.—A 6-ft. column of 23% 4-methyl-4-nitropimelonitrile on firebrick gave the best separations of the olefins. The retention times at 107°, 20 p.s.i. of pressure of helium, and a flow meter reading of 78 on the Perkin-Elmer vapor phase fractometer (Model 154) were: *trans*-2-phenyl-2-butene (III), 15 min.; 3-phenyl-1-butene (I), 20 min.; *cis*-2-butene (II), 41 min. An internal standard, *o*-bromotoluene, was used for quantitative determinations, and gave a retention time of 33 min. under the above conditions. No overlapping of peaks was observed with mixtures of the four compounds. Seven synthetic mixtures were prepared in which the relative amounts of the three olefins were varied over a wide range, and these were submitted to vapor phase chromatography. Plots of the ratio of the area of a component to the area of the internal indicator against the percentage of the component gave very straight lines. The areas under the peaks were determined with a Minneapolis-Honeywell recorder equipped with a disk chart integrator. In duplicate runs, each point could be reproduced within $\pm 0.8\%$.

Kinetic Runs.—Kinetic measurements were made on the isomerization of 3-phenyl-1-butene (I) to *cis*-2-phenyl-2-butene (II) and *trans*-2-phenyl-2-butene (III) in *tert*-butyl alcohol at $75 \pm 0.1^\circ$ with potassium *tert*-butoxide as catalyst. The ampoule technique was used. The cleaning of rate tubes, purification of solvent, and preparation of the basic solution has been described elsewhere.¹⁹ Weighed substrate I was added to the basic solution in a volumetric flask under a stream of pure nitrogen, the solution was brought to the desired volume, mixed, and a sample was withdrawn for titration of base. The rate tubes were filled with about 5 ml. of the reaction mixture, flushed with nitrogen, sealed, and placed in a constant temperature bath. At the designated times, a tube was removed, cooled, opened, and quenched with water, and the product was extracted with pure pentane several times. The combined pentane layers were washed with water, dried, and evaporated through a packed column. In the kinetic runs, the residual oil was flash distilled, a small sample was weighed, a weighed amount of *o*-bromotoluene added, and the olefins were analyzed. In the runs where the product was examined, the residual oil was passed through a preparatory vapor phase column (23% 4-methyl-4-nitropimelonitrile on firebrick) run at 65° with helium as carrier gas. After the 3-phenyl-1-butene and *cis*-2-phenyl-2-butene fractions were collected, each was dissolved in pure pentane and passed through a short plug of silica gel which was washed with pentane (drying purposes). The pentane was evaporated through a short packed column, and the residue flash distilled. In representative kinetic runs, the base in the last tube was titrated, and the concentration was found not to change during the run. The results of the kinetic run are set forth in Table VI. The rate constants were calculated based on the absolute amount of starting material recovered, assuming an 8% loss of I during the isolation procedure (see control runs).

TABLE VI

RATE OF ISOMERIZATION OF 3-PHENYL-1-BUTENE (I) TO *cis*-2-PHENYL-2-BUTENE (II) AND *trans*-2-PHENYL-2-BUTENE (III) AT $75 \pm 0.1^\circ$ IN *tert*-BUTYL ALCOHOL CATALYZED BY POTASSIUM *tert*-BUTOXIDE

Subst. concn., <i>M</i>	Base concn., <i>M</i>	Time, sec.	Composition of olefin			$10^4 \times k_1$, sec. ⁻¹	$10^4 \times k_2$, I. mole ⁻¹ sec. ⁻¹
			1	II	III		
0.424	0.398	18000	43	52	0.6	4.7	1.2
.424	.398	25200	35	62	1	4.2	1.0
.424	.398	41400	16	81	1.1	4.3	1.1
.404	.399	10800	61	30	0.7	4.7	1.2
.404	.399	32520	26	73	1.5	4.2	1.0
.414	.408	18000	42	49	1	4.8	1.2

Control Experiments.—The runs of Table II were conducted to determine if the products once formed either isomerized further,

or underwent hydrogen-deuterium exchange. Conditions of the runs approximated those of Table I. No isomerized olefin was detected in any of these runs, although as little as 0.1% could have been found. In all cases, protio substrate was used with deuterium pools in the medium. The maximum exchange observed was 2.3% (run 17). In the deuterium analysis by combustion and falling drop method,⁷ the olefin samples recovered from the runs of Table II were always compared to starting material, and the analyses were good to ± 0.003 atom of deuterium per molecule.

The possibility existed that some of II (*cis*-olefin) arose from III (*trans*-olefin) via 2-phenyl-1-butene (IV). A run was made in which a 0.4 *M* solution of IV in a 0.4 *M* solution of potassium *tert*-butoxide in *tert*-butyl alcohol was kept at 75° for 20 hr. Only IV could be detected in the product of this run using vapor phase chromatography. As little as 0.1% of II could have been observed.

To assess losses of I and II during the isolation procedures, the following experiments were performed. A solution of 0.4985 g. of I in 0.8 ml. of pentane was passed through the preparatory vapor phase chromatographic column and the olefin collected. This material was dissolved in pure pentane, and passed through a short column of silica gel, the column was washed with pure pentane, and the combined eluates were evaporated through a packed column. The residue was flash distilled to give 0.4569 g. of recovered I, 92% recovery. When 0.5112 g. of II was submitted to the same procedure, 0.4601 g. was recovered (90%).

Deuterated Solvents for Runs 1-14.—The preparations of deuterated *tert*-butyl alcohol and ethylene glycol have been described elsewhere.²⁰ Triethylcarbinol-*O-d* was prepared as follows. Pure triethylcarbinol, 60 g., was vigorously shaken for 5 min. with 60 g. of 95% deuterium oxide, and the layers were separated. The organic portion was shaken two more times with 50-g. portions of deuterium oxide (>99.5%). After the last treatment, the mixture was filtered to break the emulsion at the interface, and the layers were separated. The organic layer was dried with 15 g. of Linde Molecular Sieves and filtered through dry (baked) sodium sulfate. The filtrate was heated to 50° with clean potassium metal, and the two phases which appeared were separated. After a second treatment with potassium, the solvent was distilled, b.p. 142°, 60%. This material was analyzed by the combustion and falling drop method,⁷ and was found to contain 0.988 atom of deuterium per molecule.

Runs 1-16 of Table I.—Run 7 is typical, and is described. To 0.765 g. of *I-d* (0.88% of 1 atom of deuterium per molecule) in 12 ml. of dry *tert*-butyl alcohol was added, under a stream of purified nitrogen, 10 ml. of 0.988 *M* potassium *tert*-butoxide. The final volume was adjusted to 25 ml. with additional *tert*-butyl alcohol. The volumetric flask was vigorously shaken, the solution was placed in a heavy-walled reaction tube flushed with pure nitrogen, and sealed. After 1167 min. at 75°, the reaction mixture was submitted to the pentane extraction and preparatory vapor phase chromatographic isolation procedures to give 0.2586 g. of recovered *I-d* and 0.2552 g. of II. The recovered olefins were each shown to be free of impurities by analytical vapor phase chromatographic procedures. The rotation of recovered I was determined as a pure liquid, and each olefin was submitted to deuterium analysis by the combustion and falling drop method (see Table I). Recovered I had n^{25D} 1.5052, and recovered II had n^{25D} 1.5398.

Deviations from the above procedure are noted below. In run 1, 1.1218 g. of starting material was used; in run 2, 0.4216 g.; in run 3, 1.3229 g.

Run 4 was carried out on a larger scale, with 4.411 g. of (–)-*I-h* as starting material. Starting material recovered from the run amounted to 0.2335 g. The rotation of this material was very carefully compared to that of starting material in two different jacketed polarimeter tubes, the readings being taken in sequence. The samples in the two tubes were then switched, and no difference in the readings was observed. All readings were $\alpha^{25D} - 3.57^\circ$ ($l = 0.5$ dm., neat). The rotations were identical to at least $\pm 0.02^\circ$. Thus, less than 0.6% racemization could have occurred. Deuterium analysis by the combustion and falling drop method gave 0.058 ± 0.003 atom of deuterium per molecule. If k_e is the rate constant for isotopic exchange and k_a the rate constant for racemization, then $k_e/k_a \geq 10$. This value is calculated

(19) D. J. Cram, B. Rickborn, C. A. Kingsbury, and P. Haberfeld, *J. Am. Chem. Soc.*, **83**, 3678 (1961).

(20) D. J. Cram and B. Rickborn, *ibid.*, **83**, 2182 (1961).

$$\frac{k_e}{k_a} \geq \frac{\ln(1 - 0.055)}{\ln 3.55/3.57} \geq 10$$

Unlike the other runs, 0.02 g. of *trans*-2-phenyl-2-butene was also isolated from run 4, and submitted directly to deuterium analysis by mass spectrometry.⁸ The material contained 0.489 atom of deuterium per molecule and, therefore, the rearrangement was 51% intramolecular. From run 4, 3.372 g. of *cis*-2-phenyl-2-butene was isolated and submitted to deuterium analysis by both the combustion and falling drop method,⁷ and also by mass spectrometry.⁸ The value obtained by the former method was 0.502 and, by the latter method, 0.495 atom of deuterium per molecule. The close approach of these values to one another provides an indication of the accuracy of the analyses.

In run 5, 0.837 g. of starting material, in run 6, 1.388 g., in run 7, 0.765 g., in run 8, 1.058 g., in run 9, 1.173 g., and in run 10, 1.024 g. of starting material was used.

Runs 8, 9, and 10 involved tetramethylammonium hydroxide as base. In runs 8 and 10, tetramethylammonium hydroxide was dissolved in *tert*-butyl alcohol-*O-d* (0.976 atom of deuterium per molecule) and ordinary *tert*-butyl alcohol, respectively, and dried for 5 days over baked Linde Molecular Sieves. No water could be detected by Karl Fischer titration of the solutions after the drying process. The *tert*-butyl alcohol was evaporated at 0.01 mm. from a sample of the basic solution of run 8 and the distillate was analyzed for deuterium and found to be 0.59 atom of deuterium per molecule.

In run 9, an attempt to use deuterated base was made. Dried tetramethylammonium hydroxide (25 g.) was dissolved in 100 ml. of deuterium oxide (>99.5%) and was allowed to sit at 25° for 2 hr. The excess deuterium oxide was removed at 0.05 mm. pressure to constant weight. A solution of 2.5 g. of the base in 50 ml. of *tert*-butyl alcohol-*O-d* (0.976 atom of deuterium per molecule) was dried over baked Molecular Sieves for 4 days. Karl Fischer titrations of the solution before and after the drying indicated that the final solution was less than 0.01 *M* in water. The solution was titrated to a phenolphthalein end point with standard acid, and for trimethylamine to a brom cresol blue end point. The results demonstrated the base to be (CH₃)₄NOH·0.01(CH₃)₃N. The *tert*-butyl alcohol was evaporated at 0.01 mm. of pressure from a sample of the solution, and the distillate was analyzed for deuterium, and found to have 0.82 atom of deuterium per molecule. This solution was used in run 9. After the run was completed, the reaction mixture was shaken with 25 ml. of water and 50 ml. of pentane, and the pentane solution was treated as in run 7. The aqueous layer was thoroughly washed with pentane, and most of the water was removed under reduced pressure. The white residue was neutralized with hydrochloric acid, and again the water was removed under reduced pressure. The residue was recrystallized from a mixture of ethanol-ethyl acetate, dried, and analyzed for deuterium.⁷ The tetramethyl-

ammonium chloride contained 5.7 atoms of deuterium per molecule.

In run 11, 0.534 g. of starting material, in run 13, 0.590 g., in run 14, 0.501 g., and in run 15, 1.317 g. was used. In run 13, the olefin mixture from the reaction was submitted to direct vapor phase analysis, and found to be 83% I and 17% II (sum of the two olefins was set equal to 100%). These values compare with values calculated from the data of Table I based on final weights of I and II obtained: 88% I and 12% II (sum of the two olefins was set equal to 100%).

In run 12, 4.496 g. of (+)-I-*h* was used and the recovered starting material amounted to 1.491 g. The rotation of this material was carefully taken and found to be 5.9% racemized. Deuterium analysis by combustion and falling drop method gave 0.042 ± 0.003 atom of deuterium per molecule and, therefore, $k_e/k_a = 0.70$. About 0.07 g. of *trans*-2-phenyl-2-butene was also isolated from run 12 and submitted directly to deuterium analysis by mass spectrometry.⁸ The material contained 0.67 atom of deuterium per molecule and, therefore, the rearrangement was 33% intramolecular.

In run 16, 7.00 g. of (+)-I-*h* was used and 0.706 g. of recovered starting material was obtained. The rotation of this material was very carefully compared to that of the starting material as in run 4, and no difference of readings could be detected. The rotations were identical to at least ±0.02°.

Ozonolysis of *cis*-2-Phenyl-2-butene (II).—To determine if deuterium entered any other than the 4-position during the isomerization of I to II, the samples of II left over from analysis from runs 1, 3, 4, 6, 8, 9, and 11 were combined. Ozone was passed through a solution of 1.2 g. of this material in 15 ml. of pure pentane at 0° until a sample of the solution did not decolorize a 1% solution of bromine in carbon tetrachloride. Ether (25 ml.) was added to the solution, 3 g. of lithium aluminum hydride was added, and the reaction mixture was stirred at 25° for 12 hr. The excess hydride was decomposed with cold 6 *N* hydrochloric acid, and the aqueous phase was extracted twice with ether. The combined extracts were washed with water, saturated sodium bicarbonate solution, and again with water. The ether solution was dried, evaporated, and the residual oil was submitted to preparative vapor phase chromatography on a 5% Carbowax on firebrick column at 100° with helium as carrier gas to give 0.25 g. (20%) of α -methylbenzyl chloride, n_D^{25} 1.5252. Deuterium analysis⁷ indicated the absence of deuterium (0.002 ± 0.003 atom of deuterium per molecule).

As a control for the above experiment, the following run was made. Deuterated hydrochloric acid was prepared by distilling a mixture of phosphorus pentachloride and deuterium oxide (>99.5%) at 108°. The distillate (azeotrope) was approximately 6 *N*. A mixture of 2 g. of α -methylbenzyl alcohol in 23 ml. of this deuterated hydrochloric acid was vigorously stirred for 5 hr. at 25°. The α -methylbenzyl chloride was isolated as was the material from the ozonolysis run, 1.1 g., n_D^{25} 1.5252, 0.008 ± 0.003 atom of deuterium per molecule.⁷