solution was immediately diluted with 200 ml. of water. The yellow solid which precipitated, 1.8 g., 66%, after crystallization was identified as the β-*p*-nitrophenylhydrazone of phenylglyoxal.

Preparation of α-Phenylhydrazones of Glyoxals.—The four α-phenylhydrazones of phenylglyoxal were prepared from sodium benzoylacetate by reaction with the proper diazonium salt.[18] Similarly, *p*-nitrobenzenediazonium chloride was treated with sodium propionylacetate,[19] according to a procedure described for sodium acetoacetate,[20] to produce the α-*p*-nitrophenylhydrazone of ethylglyoxal. The α-derivatives are recorded in Table II.

Preparation of Phenylosazones of Glyoxals.—The reaction of phenylglyoxal[21] with the appropriate phenylhydrazine and the reaction of the α- and β-phenylhydrazones of the glyoxals were all done in the usual manner.[22] *p*-Methoxyphenylhydrazine was prepared by the method of Blaike and Perkin.[23] The other hydrazines were prepared by a method described for phenylhydrazine.[24]

Infrared Absorption Spectra.—The spectra were determined as solutions in carbon tetrachloride, carbon disulfide and chloroform. A Perkin–Elmer double beam, self-recording instrument, with rock salt optics throughout the region studied, was employed. Sodium chloride cells of 0.111 mm. and 0.215 mm. were used.

Acknowledgment.—We wish to express our appreciation to W. A. Blanchard and W. C. Bailey who determined the infrared spectrograms and to Drs. Leon Mandell and J. H. Goldstein who helped in their interpretation.

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[18] E. Bamberger and A. Schmidt, *Ber.*, **34**, 2015 (1901).

[19] A. Brandstrom, *Acta Chem. Scand.*, **5**, 820 (1951).

[20] F. D. Chattaway and D. R. Ashworth, *J. Chem. Soc*, 930 (1934).

[21] W. Madelung and M. E. Oberwegner, *Ber.*, **65**, 931 (1932).

[22] R. L. Shriner and R. C. Fuson, "The Systematic Identification of Organic Compounds," 3rd Ed., John Wiley and Sons, Inc., New York, N. Y., 1948, p. 171.

[23] K. G. Blaike and W. H. Perkin, *J. Chem. Soc.*, **125**, 313 (1924).

[24] Reference 16, Coll. Vol. I, p. 442.

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[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY AND CHEMICAL ENGINEERING, STANFORD UNIVERSITY, AND THE CHEMISTRY DIVISION, OAK RIDGE NATIONAL LABORATORY]

Molecular Rearrangements. X. Rearrangement During the Deamination of 1,2,2-Triphenylethylamine with Nitrous Acid[1]

BY WILLIAM A. BONNER AND CLAIR J. COLLINS

RECEIVED MAY 25, 1956

1,2,2-Triphenylethylamine, alternately labeled with radioactive carbon at carbon-1 and in the 1-phenyl nucleus, has been prepared and subjected to deamination with nitrous acid. 1,2,2-Triphenylethanol constituted over 95% of the product from these deaminations. The extent of isotope position isomerization attending the deaminations has been determined by oxidation of the carbinol products to benzophenone and benzoic acid, followed by radioactivity assay of these fragments. The net phenyl migration accompanying deamination of the carbon-1 labeled amine could be related to that observed during deamination of the 1-phenyl labeled amine using simple kinetic expressions based on the assumption of equilibrating classical 1,2,2-triphenylethylcarbonium ions as the sole reaction intermediates. The present radiochemical results thus lend strong support to the theory of equilibrating classical ions previously proposed to rationalize radiochemical data from tosylate solvolyses and dehydration reactions in the 1,2,2-triphenylethyl system.

Introduction

We have reported in earlier papers[2] the radiochemical results of the solvolytic and elimination reactions of multiply-labeled derivatives of 1,2,2-triphenylethanol (I). The reactions so studied could be divided into two classes depending upon

$Ph_2CH\overset{*}{C}HOHPh$
Ia

$Ph_2CHCHOHPh^*$
Ic

$Ph_2\overset{*}{C}{=}CHP\overset{*}{h}$
IIcd

$Ph_2\overset{*}{C}{=}\overset{*}{C}HPh$
IIab

whether or not the radiochemical isomerizations were complete. Thus the acid-catalyzed elimination reactions[2c] of Ia and Ic and their acetates yielded the olefins IIab and IIcd, respectively, which possessed statistical distributions of their radioactive labels. The isotope position isomerization of the acetates[2d] of Ia and Ic likewise proceeded to a statistical conclusion. In contrast, the acetolyses[2c] and hydrolyses[2c] of the tosylates of Ia and Ic, as well as the *p*-toluenesulfonic acid-catalyzed dehydrations (in xylene) of Ia and Ic, yielded products whose labels were not distributed statistically. Further, in all of the reactions studied there was a higher percentage rearrangement of the phenyl label than of the chain label.

The concept of bridged ions as intermediates[3] in certain molecular rearrangements very satisfactorily accounts for the stereochemistry and kinetics observed, particularly in those cases studied by Cram[3c] in which the rate-determining ionization is assisted by the migrating group. The observed radiochemical[2c,d] results for the rearrangement of 1,2,2-triphenylethanol and its derivatives, in contrast, are best explained by assuming that the

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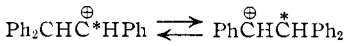
[1] This paper is based in part upon work performed under Contract Number W-7405-eng-26 for the Atomic Energy Commission at Oak Ridge National Laboratory. Paper IX, B. M. Benjamin and C. J. Collins, THIS JOURNAL, **78**, 4329 (1956).

[2] (a) W. A. Bonner and C. J. Collins, THIS JOURNAL, **75**, 5372 (1953); (b) C. J. Collins and W. A. Bonner, *ibid.*, **75**, 5379 (1953); (c) **77**, 92, 6725 (1955); (d) W. A. Bonner and C. J. Collins, *ibid.*, **77**, 99 (1955).

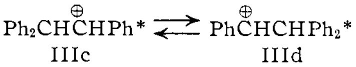
[3] (a) I. Roberts and G. E. Kimball, THIS JOURNAL, **59**, 947 (1937); (b) S. Winstein and H. J. Lucas, *ibid.*, **61**, 1576 (1939); (c) D. J. Cram and co-workers, *ibid.*, **71**, 3863, 3871, 3875 (1949); **74**, 2129, 2137, 2159 (1952); **75**, 3189 (1953); (d) S. Winstein, M. Shatavsky, C. Norton and R. B. Woodward, *ibid.*, **77**, 4183 (1955).

equilibrating, isomeric ions IIIa and IIIb, IIIc and IIId are the sole cationic intermediates.[4]



$$\mathrm{Ph_2CH\overset{\oplus}{C}{}^*HPh} \rightleftarrows \mathrm{Ph\overset{\oplus}{C}H\overset{*}{C}HPh_2}$$

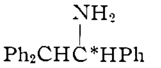
IIIa IIIb



$$\mathrm{Ph_2CH\overset{\oplus}{C}HPh^*} \rightleftarrows \mathrm{Ph\overset{\oplus}{C}HCHPh_2^*}$$

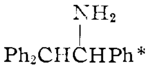
IIIc IIId

We have now extended our studies to the nitrous acid deamination of doubly-labeled 1,2,2-triphenylethylamine (IV), since it appeared that this reaction should be free from the complications of internal return.[5]



$$\mathrm{Ph_2CH\overset{NH_2}{\overset{|}{C}}{}^*HPh}$$

IVa



$$\mathrm{Ph_2CH\overset{NH_2}{\overset{|}{C}}HPh^*}$$

IVc

Methods and Results

The chain IVa and ring IVc labeled 1,2,2-triphenylethylamines were prepared by the reduction of the appropriately labeled phenyl benzhydryl ketoximes with sodium in ethanol. The structure of IVa was shown by its oxidation, with permanganate, to non-radioactive benzophenone. Deaminations were accomplished at 5° by addition of sodium nitrite to dilute acetic acid solutions of the amine hydrochlorides. The deamination product was 1,2,2-triphenylethanol (I) which contained on chromatographic investigation not more than 4% of extraneous material, presumably triphenylethylene. Redistribution of the radioactivity in the 1,2,2-triphenylethanol products was determined, as before,[2a] by oxidation of the products to benzoic acid and benzophenone, followed by radiochemical assay of the oxidized fragments as suitable derivatives.

As do[2c] the dehydration of 1,2,2-triphenylethanol and the acetolysis or hydrolysis of 1,2,2-triphenylethyl *p*-toluenesulfonate, the deamination of 1,2,2-triphenylethylamine provides an example of a reaction in which the redistribution of the radioactive label does not achieve a statistical value. As seen in Table I, 26.2% of the radioactivity migrates during deamination of the chain-1 labeled amine, whereas 29.1% net migration occurs during deamination of the 1-phenyl labeled isomer. These two deaminations were carried out under experimental conditions with respect to time, temperature, concentration and reagents which were as identical as it was possible for us to employ. During several experiments, however, in which such precautions were not taken, it was found that the extent of rearrangement of the chain label was as high as 29.6%. Because of this large variation with small changes in experimental conditions, it was necessary to carry out the deamination with a mixture of the two amines IVa and IVc. By a suitable degradation scheme (Chart I), it was possible to determine the isotope position isomerization attending the deamination of each amine in the mixture, and to eliminate the possibility of uncontrolled experimental variables which might produce spurious results. As seen in Table II, the extent of label migration attending the deamination of the carbon-1 labeled component IVa of the doubly-labeled amine was 28.2%, while that for the 1-phenyl labeled component IVc was 31.8%. The importance of the data of Table II is that the two differently labeled amines were deaminated in *the same reaction vessel*, and thus the experimental conditions were identical for both isotope position iso-

TABLE I

RADIOACTIVITY REDISTRIBUTION DURING DEAMINATION OF RADIOACTIVE 1,2,2-TRIPHENYLETHYLAMINE SERIES

Carbon	Relative radioactivity, labeled originally at Carbon-1	Relative radioactivity, labeled originally at 1-Phenyl nucleus
Phenyl benzhydryl ketone	1.000	1.000
1,2,2-Triphenylethylammonium chloride	1.003	...
1,2,2-Triphenylethanol	1.000	...
Benzophenone 2,4-dinitrophenylhydrazone	0.262	0.291
Rearrangement, %	26.2	29.1

TABLE II

RADIOACTIVITY REDISTRIBUTION DURING DEAMINATION OF DOUBLY-LABELED 1,1,2-TRIPHENYLETHYLAMINE

Reaction	Radioactivity, mc./mole
Phenyl benzhydryl ketone-C^{14}	1.133
Phenyl-C^{14} benzhydryl ketone	0.605[a]
Phenyl-C^{14} ketone-C^{14} 2,4-dinitrophenylhydrazone	.513
Acetylaniline-C^{14}	.0963

Phenyl-C^{14} migration $0.0963 \times 2/0.605 = 0.318$

Carbon-1-C^{14} migration $(0.513 - 0.193)/1.133 = 0.282$

[a] Prevailing radioactivity level *after* mixing the two ketones quantitatively.

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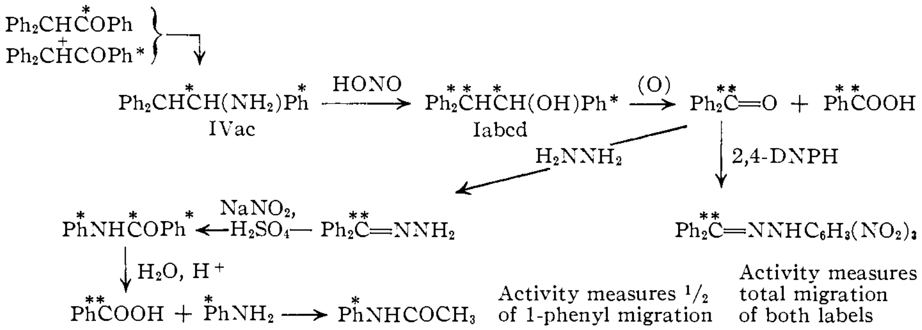
(4) The referee has commented that "the present system is distinctly less favorable on all counts for the non-classical ions to be of comparable stability to their open ions" and further has expressed the opinion that our present and previous (ref. 2) work might be "quoted as evidence against non-classical ions in general." We have felt that the evidence for phenonium ions (ref. 3c) and other types of bridged ions (ref. 3a, 3b, 3d) speaks for itself, and should require no comment on our part. It now seems desirable, however, to make our position clear regarding the bridged-ion hypothesis: The well-known work quoted in ref. 3c, as well as much other work of Cram and his co-workers, is adequately explained by assuming that phenonium ions are the intermediates. Our own radiochemical work on the reactions of 1,2,2-triphenylethanol and its derivatives is satisfactorily explained by assuming that equilibrating, classical carbonium ions are the intermediates. In each case, the least complicated mechanism consistent with all of the facts has been employed. The 1,2,2-triphenylethyl system, as pointed out by the referee, is one which might be expected, on the basis of present knowledge and theory, to provide open carbonium ions, highly stabilized by the adjacent phenyl, thus participation by neighboring phenyl would not be anticipated. This situation is in contrast to most of the systems studied by Cram, in which assistance by the migrating group is required to effect the ionizations, and thus, according to present knowledge, bridged ions are expected to be the intermediates. No one mechanism can be applied to all solvolytic, elimination, and deamination reactions (see the discussion of S. Winstein and E. Grunwald, THIS JOURNAL, **70**, 830 (1948)), therefore our results should not be generalized as evidence against the existence of bridged or "non-classical" ions in cases where they are strongly supported by the experimental facts. For an example of reactions which can be explained on the basis of a combination of open and bridged ions, see D. J. Cram and J. D. Knight, *ibid.*, **74**, 5843 (1952). For an example in which phenonium-ion intermediates have been employed to explain the dehydration of *trans*-2-phenylcyclohexanol, see H. J. Schaeffer and C. J. Collins, *ibid.*, **78**, 124 (1956).

(5) (a) S. Winstein and D. Trifan, THIS JOURNAL, **74**, 1154 (1952); (b) S. Winstein and K. C. Schreiber, *ibid.*, **74**, 2165, 2171 (1952); (c) S. Winstein and R. Heck, *ibid.*, **74**, 5584 (1952); D. J. Cram, *ibid.*, **74**, 2129, 2137, 2195 (1952).

mers. The greater extent of rearrangement in the phenyl labeled as compared to the chain-labeled product, is, therefore, a real phenomenon, and not the result merely of inadequate control of the reaction conditions.

CHART I

DEGRADATION SCHEME FOR THE DEAMINATION OF DOUBLYL-LABELED 1,2,2-TRIPHENYLETHYLAMINE

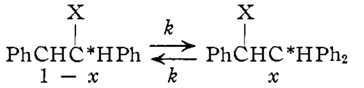


Discussion

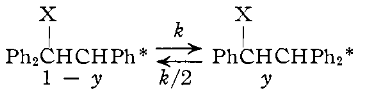
By means of a simple kinetic treatment[6] applicable to equilibria in general, we have been able to relate the net migration of the chain label to that of the ring label in reactions of 1,2,2-triphenylethanol (Ia and Ic) and its tosylate.[2c] The final equation 1 which related the redistributions of the two labels is

$$\frac{1}{2}\log\frac{0.500}{0.500-x} = \frac{2}{3}\log\frac{0.667}{0.667-y} \qquad (1)$$

in which x and y are, respectively, the mole fractions of isomerized product in the chain-1 and 1-phenyl labeled series. Equation 1 was derived[2c] by making the assumption, without regard to overall mechanism, that the chain and ring labels approached equilibrium as shown in eq. 2 and 3.



$$\underset{1-x}{\mathrm{PhCH}\overset{\mathrm{X}}{\overset{|}{\mathrm{C}}}\mathrm{{}^*HPh}} \;\underset{k}{\overset{k}{\rightleftarrows}}\; \underset{x}{\mathrm{Ph}\overset{\mathrm{X}}{\overset{|}{\mathrm{C}}}\mathrm{HC^*HPh_2}} \qquad (2)$$



$$\underset{1-y}{\mathrm{Ph_2}\overset{\mathrm{X}}{\overset{|}{\mathrm{C}}}\mathrm{HCHPh^*}} \;\underset{k/2}{\overset{k}{\rightleftarrows}}\; \underset{y}{\mathrm{Ph}\overset{\mathrm{X}}{\overset{|}{\mathrm{C}}}\mathrm{HCHPh_2^*}} \qquad (3)$$

Implicit in these equations is the further assumption that each of the two phenyl groups of the rearranged structure (eq. 3) have equal opportunities to migrate. This concept is compatible with the classical carbonium ion mechanism, but incompatible[2c] with the intervention of bridged ions[3]—with or without internal return[5]—as the sole reaction intermediates. It was of immediate interest to apply eq. 1 to the radiochemical data for the deamination reaction. In Table III the results of such calculations are compared with those obtained in our previous studies.[2c] It is apparent that eq. 1 relates the extent of label redistribution during the deamination of chain and ring-labeled 1,2,2-triphenylethylamine with about the same precision as it did in the solvolysis and dehydration reactions to which it had previously been applied.

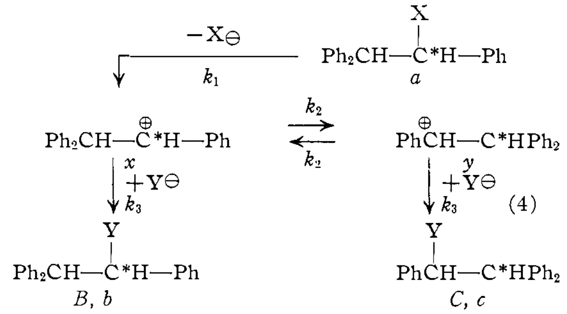
TABLE III

PREDICTED C-1 LABEL REDISTRIBUTION BASED ON EQ. 1

Reaction	Net phenyl migration, % 1-Phenyl labeled series Found	C-1 labeled series Predicted		
		Predicted	Found	Discrepancy
Deamination of 1,2,2-triphenylethylamine[a]	29.1	26.7	26.2	+0.5
Deamination of 1,2,2-triphenylethylamine[b]	31.8	29.0	28.2	+0.8
Hydrolysis of 1,2,2-triphenylethyl tosylate	23.6	22.2	22.2	0.0
Acetolysis of 1,2,2-triphenylethyl tosylate	47.1	40.3	39.5	+0.8
Dehydration of 1,2,2-triphenylethanol	60.2	47.7	47.9	−0.2

[a] For separately run amine deamination; [b] For doubly-labeled amine deamination.

Let us now consider one possible specific mechanism for reactions of the type given in Table III, and illustrate with a C-1 label. Let us assume that each step in mechanism 4 is either first order or pseudo-first order.



(4)

Let a, b, c, x and y be the instantaneous concentrations of the indicated species during any stage in the reaction, and let B and C be the final concentrations of the isomeric products, or, equivalently, the fraction of each isomer in the reaction product. Then

$$\frac{\mathrm{d}y(t)}{\mathrm{d}t} = k_2x(t) - k_2y(t) - k_3y(t) \qquad (5)$$

$$\frac{\mathrm{d}b(t)}{\mathrm{d}t} = k_3x(\ ) \qquad (6)$$

$$\frac{\mathrm{d}c(t)}{\mathrm{d}t} = k_3y(t) \qquad (7)$$

We now integrate eq. 5 between $t = 0$ and $t = \infty$, bearing in mind that at $t = 0$ and $t = \infty$ the concentrations x and y are zero.

$$\int_0^\infty (\mathrm{d}y/\mathrm{d}t)\mathrm{d}t = 0 = k_2\int_0^\infty x(t)\,\mathrm{d}t - k_2\int_0^\infty y(t)\,\mathrm{d}t - k_3\int_0^\infty y(t)\,\mathrm{d}t \qquad (8)$$

We next replace $\int_0^\infty x(t)\,\mathrm{d}t$ and $\int_0^\infty y(t)\,\mathrm{d}t$ by their respective "integration areas,"[7] S_x and S_y, so that (8) becomes

$$k_2S_x - k_2S_y - k_3S_y = 0 \qquad (9)$$

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(6) K. J. Laidler, "Chemical Kinetics," McGraw-Hill Book Co., Inc., New York, N. Y., p. 20.

and

$$\frac{S_x}{S_y} = \frac{k_2 + k_3}{k_2} \qquad (10)$$

Again using the "Area Theorem"[7] we find for (6) and (7)

$$\int_0^\infty (\mathrm{d}b/\mathrm{d}t)\mathrm{d}t = B = k_3\int_0^\infty x(t)\ \mathrm{d}t = k_3S_x \qquad (11)$$

$$\int_0^\infty (\mathrm{d}c/\mathrm{d}t)\mathrm{d}t = C = k_3\int_0^\infty y(t)\ \mathrm{d}t = k_3S_y \qquad (12)$$

and

$$\frac{B}{C} = \frac{k_3S_x}{k_3S_y} = \frac{k_2 + k_3}{k_2} = 1 + \frac{k_3}{k_2} \qquad (13)$$

in which B/C is the ratio of unrearranged to rearranged product.

A similar treatment for the 1-phenyl labeled series of experiments may be carried out, bearing in mind that the specific rate constants for the ion equilibration step are k_2 in the forward and $k_2/2$ in the reverse direction.[2c] For the 1-phenyl labeled case we find

$$\frac{B'}{C'} = \frac{k_2/2 + k_3}{k_2} = \frac{1}{2} + \frac{k_3}{k_2} \qquad (14)$$

in which B'/C' is the ratio of unrearranged to rearranged product in the 1-phenyl labeled series. Equating the expressions for k_3/k_2 in (13) and (14), we obtain (15), which reduces to (18) when eq. 16 and 17 are introduced

$$\frac{B - C}{C} = \frac{2B' - C'}{2C'} \qquad (15)$$

$$B = 1 - C \qquad (16)$$

$$B' = 1 - C' \qquad (17)$$

$$\frac{1 - 2C}{C} = \frac{2 - 3C'}{2C'} \qquad (18)$$

Equation 18 thus arises as an application of the "Area Theorem" to the rate expressions for mechanism (4). Such a derivation is perfectly general, and requires no postulates as to the relative magnitudes of k_1, k_2 or k_3. Equation 18 emerges alternatively, but less rigorously, by the application of a slightly modified steady state treatment to equations 5, 6 and 7. The application of eq. 18 to our radiochemical data permits a test of the general applicability of mechanism (4) to the reactions studied. In Table IV, C, the fraction of rearranged product in the chain-1 labeled series is predicted from C', that in the 1-phenyl labeled series, using equation 18. It is seen that eq. 18 permits a relation of the extents of phenyl migration in the chain-1 labeled experiments with fair accuracy.

As has been pointed out,[2c] the only way in which bridged ionic intermediates could, qualitatively at least, explain the radiochemical results observed during solvolyses of 1,2,2-triphenylethyl tosylate would be that (a) *cis*- and *trans*-phenonium ions were formed with equal probability (no stereospecificity) and simultaneously that (b) the rate of internal return[5] to isomerized reactant from such phenonium tosylate ion pairs be much greater than the rate of product formation from such ion pairs.

TABLE IV

PREDICTED C-1 LABEL REDISTRIBUTION BASED ON REACTION MECHANISM (4)

	Net phenyl migration, %			
	1-Phenyl labeled series (C')	C-1 labeled series (C)		
	Found	Predicted	Found	Discrepancy
Deamination of 1,2,2-triphenylethylamine[a]	29.1	25.1	26.2	−0.8
Deamination of 1,2,2-triphenylethylamine[b]	31.8	27.4	28.2	−0.8
Hydrolysis of 1,2,2-triphenylethyl tosylate	23.6	21.1	22.2	−1.1
Acetolysis of 1,2,2-triphenylethyl tosylate	47.1	38.1	39.5	−1.4
Dehydration of 1,2,2-triphenylethanol	60.2	46.3	47.9	−1.6

[a] For separately run amine deamination. [b] For doubly-labeled amine deamination.

The presence of internal return, however, is most unlikely in the deamination of 1,2,2-triphenylethylamine, for in this instance it is probable that carbonium ions such as IIIa are generated irreversibly by loss of nitrogen from their unstable diazonium ion precursors.[8]

On examination of eq. 2 and 3 it can be seen that if the functional group "X" represents *p*-toluenesulfonate, then these equations express the process of internal return[5] *via* classical carbonium ion intermediates for the tosylates of chain and ring-labeled 1,2,2-triphenylethanol. In the event that the rates of solvolysis of these tosylates were negligible, then eq. 1 should relate exactly the fraction of chain-label rearrangement (x) to the fraction of ring-label rearrangement (y). Alternately it is apparent that mechanism (4) represents solvolysis (or deamination) in the *absence* of internal return,[5] and that eq. 18 therefore should relate exactly the fraction of chain-label rearrangement (C) to the fraction of ring-label rearrangement (C') under these conditions. Any mechanism which involves equilibrating classical carbonium ions (IIIa $\rightleftarrows$ IIIb; IIIc $\rightleftarrows$ IIId) as the sole cationic intermediates for the reactions of Tables III and IV should, therefore, require the radiochemical consequences of these reactions to be described by eq. 1 and 18 as *limiting* relations. If no reversible processes such as internal return[5] take place during a given reaction, then the fractions of rearrangement of the chain and ring labels should be related as predicted by eq. 18. If reversible processes such as internal return do take place then the fractions of rearrangement of the chain and ring labels should be no closer together than predicted by eq. 1. That the radiochemical results of all of the reactions of Tables III and IV are related by eq. 1, or are intermediate between the consequences predicted by eq. 1 and 18, may therefore be taken as compelling evidence for the validity of the equilibrating classical carbonium ion mechanism. It is

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[7] We are indebted to Dr. J. Z. Hearon for his aid in interpreting mechanism 4 in terms of his "Area Theorem." For previous application of this theorem, see B. M. Benjamin and C. J. Collins, THIS JOURNAL, **78**, 4329 (1956).

[8] L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, p. 295; A. R. Day, "Electronic Mechanisms of Organic Reactions," American Book Company, New York, N. Y., 1950, p 225-226.

clear, from the same argument, that bridged ions alone cannot be intermediates in these reactions.[9]

It might be expected that the fractions of chain and ring labels which are rearranged during the deamination reaction should be related exactly by eq. 18 if our classical carbonium ion mechanism is correct, since internal return should not take place during this reaction. The differences between the observed extents of rearrangement of the two labels and those predicted from eq. 18 (Table IV) are greater than the experimental error of the method of *radioactivity assay* used (about ± 0.5%). The experimental error in the entire degradative sequence (Chart I) is difficult to assess, however, and may be somewhat greater than the error of the assay method alone. An additional clue as to the reasons why none of the rearranged chain and ring labels (Table IV) differ as much as predicted by Eq. 18 is to be found in the stereochemistry of these same reactions, which will be the subject of a future paper.

The reactions of Tables III and IV may be considered from the viewpoint of a simple energy diagram (Fig. 1). Reactant R passes through an initial transition state T_1, falling to one of the classical ion intermediates (IIIa); IIIa may then pass through a final transition state T_3, giving unrearranged product P, or may follow an alternate path over T_2 to the isomeric ion (IIIb). The latter may then go through an equivalent final transition state T_3' to the isomerized product P′, it may pass over T_1' to yield isomerized reactant R_1' or it may return back over T_2 to IIIa. The relative heights of the transition states T_2 and T_3, T_3' above the IIIa, IIIb valleys will determine the extent of isomerization attending a given reaction. While the T_2 barrier height is presumably more or less constant, the T_3, T_3' barrier height will vary from one reaction to another. Thus, when the energy corresponding to T_3, T_3' is much greater than that corresponding to T_2, complete radiochemical equilibration will occur before T_3 or T_3' have been crossed, while equilibration will obviously be incomplete where the heights of T_2 and T_3, T_3' are approximately the same. When the T_1, T_1' barriers are sufficiently above the T_3, T_3' barriers, then passage from IIIa or IIIb back over T_1 to R is improbable, and no internal return occurs. When the T_1, T_1' barriers are lower than the T_3, T_3' barriers, then internal return will be rapid compared to the rate of product formation.

Future papers will deal with the stereochemical consequences of the deamination of optically active, labeled 1,2,2-triphenylethylamine, with the hydrolysis and acetolysis of optically active 1,2,2-triphenylethyl tosylate, and with the rate of racemization of optically active 1,2,2-triphenylethyl acetate under conditions previously employed[2d] for its isotope position isomerization.

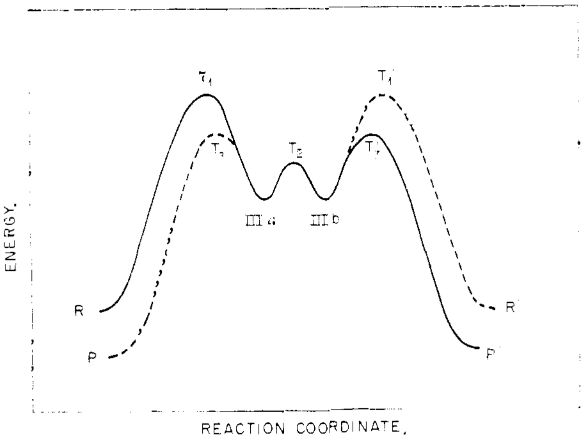

Fig. 1.

Experimental

Phenyl Benzhydryl Ketoxime.—Phenyl benzhydryl ketone (2.5 g.) and hydroxylamine hydrochloride (3.5 g.) were dissolved in a hot mixture of pyridine (12.5 ml.) and ethanol (12.5 ml.). The solution was heated under reflux for 4.5 hours, whereupon the solvents were evaporated in an air stream at 100°. The dry material was broken up, leached with water and filtered. The residue was recrystallized (Norit) from dilute ethanol to produce 1.8 g. of product, m.p. 149–151° (with preliminary softening). After three additional recrystallizations from ethanol the product had m.p. 173.5° in agreement with the literature.[10] In later, larger scale preparations, the crude oxime was extracted into ether solution. After being washed with water, dilute hydrochloric acid and water, then being dried (anhydrous sodium sulfate), the ether was evaporated, leaving behind nearly quantitative yields of crude oxime. Such preparations were reduced to triphenylethylamine without further purification.

1,2,2-Triphenylethylammonium Chloride.—Phenyl benzhydryl ketoxime (10.2 g.) was dissolved in refluxing absolute ethanol (220 ml.). Through the condenser and into the refluxing solution, pieces of sodium (21 g.) were added slowly. A little more ethanol was added toward the end of the reduction. When the sodium had reacted completely, a solution of hydrochloric acid (190 ml.) in water (1000 ml.) was added to the reaction mixture. The solution was heated on the steam-bath for three hours while air was bubbled through to remove the ethanol, then was cooled. The solid was filtered, then redissolved, in hot water (300 ml.). The solution was cooled, filtered (Celite) and extracted once with benzene (discard); evaporation of this extract yielded small amounts of phenyl benzhydryl ketoxime, unreacted in the preceding reduction. The aqueous layer was combined with the above aqueous filtrate, and the mixture was concentrated to *ca.* 350 ml. in an air stream at 100°, whereupon it was chilled. The crude amine hydrochloride which precipitated weighed 10.5 g. (95.5%). It was purified by dissolving in water (200 ml.), filtering the solution through Norit, adding hydrochloric acid (30 ml.), and chilling to reprecipitate 7.3 g. of product. Final purification was accomplished by vacuum sublimation (230°/1 mm.), followed by exposure of the sublimate to hydrogen chloride fumes. The purified 1,2,2-triphenylethylammonium chloride had m.p. 244–245° (with sublimation).

Anal. Calcd. for $C_{20}H_{20}NCl$: C, 77.59; H, 6.51; N, 4.53. Found: C, 77.68; H, 6.41; N, 4.41.

1,2,2-Triphenylethylamine Acetate.—The acidic mother liquors from the above amine hydrochloride preparation were made alkaline, and the mixture was extracted with ether. After washing and drying the ether extract, solvent removal left 0.4 g. of crude 1,2,2-triphenylethylamine, a heavy oil. This was treated with acetic anhydride (15 ml.), and the mixture was heated for 1.5 hours, then cooled and treated with excess water. After hydrolysis, the mixture was extracted with ether, and the acetylated amine isolated on evaporation of the extract. Several recrystallizations

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[9] As was indicated in a prior paper (ref. 2c) the possibility that the isomerizations IIIa ⇄ IIIb, IIIc ⇄ IIId take place through bridged ionic intermediates cannot be ruled out; in the absence of any definite experimental evidence for their existence, however, such bridged intermediates are unnecessary in the present explanation. See, however, ref. 4.

[10] E. P. Kohler and J. F. Stone, Jr., THIS JOURNAL, **52**, 761 (1930).

(Norit) from ethanol gave pure 1,2,2-triphenylethylamine acetate, m.p. 205–206°.

Anal. Calcd. for $C_{22}H_{21}ON$: C, 83.78; H, 6.71; N, 4.44. Found: C, 83.75, 83.81; H, 6.88, 6.89; N, 4.13.

Deamination of 1,2,2-Triphenylethylamine.—Once recrystallized 1,2,2-triphenylethylammonium chloride (7.11 g.) was dissolved in hot water (355 ml.). The solution was cooled, filtered (Celite) and treated with acetic acid (10 ml.), then chilled in ice to 5°. To the cold, stirred solution was added dropwise over a five-minute period a solution of sodium nitrite (15.2 g.) in water (152 ml.). After addition, the mixture was stirred at room temperature for 25 min., then was made alkaline by addition of concd. sodium hydroxide solution. The mixture was extracted four times with C.P. ether, and the extracts were washed, dried and decolorized by filtration through a Norit bed. Solvent removal from the filtrate yielded 5.88 g. (93%) of crude 1,2,2-triphenylethanol. This was recrystallized from a mixture of acetic acid (18 ml.) and water (5 ml.), producing 4.37 g. of pure product, m.p. 83–84.5°.

In another experiment 0.28 g. of crude 1,2,2-triphenylethanol from a similar deamination was dissolved in ligroin, and the solution was passed through a 1 × 22 cm. alumina column, rinsing well with ligroin. Evaporation of the effluent left 0.01 g. of residue, unidentified but presumably 1,2,2-triphenylethylene. The column was rinsed with methanol (40 ml.), evaporation of which gave 0.27 g. of amber oil which was crystallized and characterized as the carbinol. The deamination of 1,2,2-triphenylethylamine thus appears to produce about 96% carbinol and less than 4% olefin.

Radioactive Experiments.—Preparations and reactions involving radioactive 1,2,2-triphenylethylamine were conducted exactly as described above, using proportional reagent quantities when the run size was altered. All experiments were conducted under as closely standardized conditions as possible. Starting materials in these cases were analytically pure samples of phenyl benzhydryl ketone having the carbon-14 label either in the carbonyl carbon or randomly in the 1-phenyl ring.[2c] All products were purified to analytical purity prior to radioactivity assay. Label distribution in the final radioactive 1,2,2-triphenylethanol deamination products was assessed, as before, by oxidation of these products to benzophenone and benzoic acid using potassium permanganate in dilute, acidified acetone,[2a,2c] then assaying purified samples of the benzoic acid and benzophenone 2,4-dinitrophenylhydrazone. Radioactivity assays were conducted in a previously described fashion.[2] In Table V are summarized the pertinent radiochemical data.

Table V

Data Pertaining to Synthesis and Deamination of Radioactive 1,2,2-Triphenylethylamine Samples

Compound	Radioactivity,[a] mc./mole C^{14} Label at Carbon-1	1-Phenyl nucleus
Phenyl benzhydryl ketone	2.192 ± 0.008	0.4965 ± 0.001
1,2,2-Triphenylethylammonium chloride	2.200	. . .
1,2,2-Triphenylethylamine acetate	2.178	. . .
1,2,2-Triphenylethanol	2.191	. . .
Benzophenone 2,4-dinitrophenylhydrazone[b]	0.5745 ± 0.0051	0.1443 ± 0.0015
Benzoic acid[c]	1.562	0.3355

[a] Critical assays (phenyl benzhydryl ketone and benzophenone 2,4-dinitrophenylhydrazone) were always run at least in duplicate or triplicate, as were other assays where precision is indicated. [b] Assays of the benzoic acid resulting on oxidation of 1,2,2-triphenylethanol were, as reported and rationalized before,[2a] uniformly low. Migration data are therefore again calculated from the more reliable benzophenone 2,4-dinitrophenylhydrazone assays.

Deamination of Doubly-Labeled 1,2,2-Triphenylethylammonium Chloride.—A sample of doubly-labeled phenyl benzhydryl ketone was prepared by quantitatively mixing 5.857 g. of phenyl benzhydryl ketone-1-C^{14} with 5.434 g. of phenyl-C^{14} benzhydryl ketone.

The mixed ketone (9.90 g.) was converted as above to crude ketoxime, 10.2 g. (98%). The latter was reduced to the crude doubly-labeled amine hydrochloride, 10.5 g. (95.5%) as described above. The crude product was dissolved in boiling water (200 ml.), filtered (Norit) and the filtrate was treated with concd. hydrochloric acid (30 ml.) and chilled in ice. The purified product was collected and air-dried, 7.3 g. (66%). Purification of a sample for assay was accomplished by vacuum sublimation (230°/0.1 mm.), followed by exposure of the sublimate to hydrogen chloride fumes for two days.

The mother liquors from the above recrystallization were made alkaline, extracted with ether, and the extract was processed for crude amine recovery, 0.40 g. The recovered sample was converted to its acetate as described before, then purified by two recrystallizations from dilute ethanol followed by vacuum sublimation prior to its assay.

The recrystallized doubly-labeled 1,2,2-triphenylethylammonium chloride above (7.11 g.) was dissolved in hot water (355 ml.). The filtered solution was acidified with acetic acid (10 ml.), chilled to 5°, and treated with stirring over five minutes with a solution of sodium nitrite (15.2 g.) in water (152 ml.). After stirring for 25 min. at room temperature, the reaction mixture was processed as described above for 1,2,2-triphenylethanol, 5.88 g., (93%). The crude product was crystallized from a mixture of acetic acid (18 ml.) and water (5 ml.), giving 4.37 g. of pure product (Iabcd), m.p. 83–84.5° after drying in air for 15 hours. A small sample was recrystallized again from acetic acid, then dried *in vacuo* over phosphoric anhydride and sodium hydroxide prior to assay. The mother liquors above were worked for a second crop, 0.95 g. This was recrystallized from dilute acetic acid to give 0.51 g. which was combined with the recrystallized sample above. The entire sample was dried *in vacuo* over P_2O_5 and NaOH prior to its degradation below.

Table VI

Radioactivity Assays Pertaining to the Deamination of Doubly-labeled 1,2,2-Triphenylethylammonium Chloride

Compound	Assay, mc./mole
Phenyl benzhydryl ketone-1-C^{14}	2.185 ± 0.004
Phenyl-C^{14} benzhydryl ketone	1.258 ± 0.003
1-Phenyl-C^{14}-2,2-diphenylethyl-1-C^{14}-ammonium chloride[a]	1.744
1-Phenyl-C^{14}-2,2-diphenylethyl-1-C^{14}-amine acetate[a]	1.718
Phenyl-C^{14} phenyl ketone-C^{14} 2,4-dinitrophenylhydrazone	0.5125 ± 0.0027
Acetylaniline-C^{14}	0.09625 ± 0.00025

[a] Compare with 1.739 mc./mole calculated as total radioactivity on mixing the indicated quantities of the two ketones.

Degradation of Doubly-labeled Deamination Product Iabcd.—The carbinol Iabcd (3.85 g.) from the foregoing deamination was dissolved in 96 ml. of glacial acetic acid, and to it was added 3.85 g. of chromic anhydride in 5 ml. of acetic acid and 10 ml. of water. The mixture became warm; it was allowed to stand for one hour, then was cooled in an ice-bath. The benzhydryl phenyl ketone which separated was filtered, and the filtrate was poured into water, from which additional ketone was obtained. The combined yield of ketone was 3.54 g. (93% of theory). In the filtrate there remained benzophenone and benzoic acid from the further oxidation of the ketone. These were isolated and saved, to be combined with the benzophenone and benzoic acid fractions obtained as described below.

The ketone (3.54 g.) was dissolved in 15 ml. of acetic acid and to it was added 3.75 ml. of concd. nitric acid. The mixture was boiled gently for 15 min., then cooled and to it was added 3.85 g. of chromic anhydride in 5 ml. of water and 10 ml. of acetic acid. This was allowed to warm on a steam-bath for one hour, after which time the mixture was poured into water. The benzophenone and benzoic acid fractions were separated, and combined with the respective fractions obtained previously as by-products during the oxidation of 1,2,2-triphenylethanol to benzhydryl phenyl ketone. The yield of benzoic acid was quantitative. An aliquot of the benzophenone fraction was converted to its 2,4-dinitrophenylhydrazone. From the yield of derivative it was calculated that the over-all yield of benzophenone from 1,2,2-triphenylethanol was 90%. Radioactivity assay of benzoic acid, 1.200 ± 0.014 mc./mole. Radioactivity assay of purified benzophenone 2,4-dinitrophenylhydrazone, 0.5125 ± 0.0027 mc./mole. These two assays total 1.713 ± 0.017 mc./mole (compared with a calculated value of 1.739 mc./mole for the doubly-labeled amine). According to Pearson and Greer,[11] 2.20 g. of benzophenone hydrazone prepared from the foregoing benzophenone was dissolved in 45 ml. of concd. H_2SO_4. The solution was cooled to 5°, and 820 mg. of $NaNO_2$ was slowly added, the mixture being stirred all the while. After about one hour all of the $NaNO_2$ had been added during which time the temperature had been maintained below 8°. The solution was poured onto ice, and the resulting mixture was neutralized with ammonium hydroxide. The crude benzanilide was filtered to yield 2.08 g. of product after desiccation. A portion of this benzanilide (1.5 g.) was boiled for 30 minutes with 20 ml. of 50% (by volume) sulfuric acid. The cooled mixture was extracted with ether. The aqueous layers were carefully and slowly neutralized with sodium hydroxide, and then extracted with ether. The fraction containing the aniline was concentrated, then acetylated by boiling with acetic anhydride to yield 683 mg. (66%) of acetanilide. The benzoic acid fraction weighed 613 mg. (66%). Radioactivity assay of acetanilide, purified by repeated crystallization from benzene, 0.09625 ± 0.00025.

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[11] D. E. Pearson and C. M. Greer, *ibid.*, **71**, 1895 (1949).

[CONTRIBUTION FROM ROHM AND HAAS CO., REDSTONE ARSENAL RESEARCH DIVISION]

Primary and Secondary Isotope Effects in the Enolization of Ketones

BY WILLIAM D. EMMONS AND M. FREDERICK HAWTHORNE

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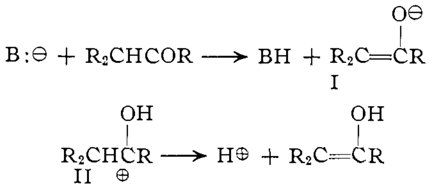
Primary and secondary isotope effects have been determined for the acid- and base-catalyzed rates of enolization of phenyl cyclopentyl and phenyl cyclohexyl ketones. The α-deutero and the $\beta,\beta,\beta',\beta'$-tetradeuteroketones were prepared by standard methods and their enolization rates were determined by using a spectrophotometric bromination procedure. The rates were all obtained in an acetic acid–water solution using sodium acetate as the catalyst for the base-catalyzed rates and hydrochloric acid as catalyst for the acid-catalyzed rates. The observed isotope effects are discussed in terms of previous work on secondary isotope effects in chlorosulfite solvolysis and offer rather striking evidence that Swain's termolecular picture of ketone enolization is correct. The importance of a steric factor in ketone enolization is also pointed out and the Hughes–Ingold picture of ketone enolization is refuted in part.

In recent years two somewhat different pictures of acid- and base-catalyzed enolization of ketones have been presented. Thus the Hughes–Ingold school[1] has proposed that the base-catalyzed enolization of a ketone proceeds through the enolate anion I whose formation is controlled largely by inductive effects of the alkyl groups. The acid-catalyzed enolization is believed by this group to involve the removal of a proton from the conjugate acid of the ketone II and this process is dependent chiefly on hyperconjugation by the alkyl groups in the transition state for the formation of the carbon–carbon double bond. Evidence cited in favor of these concepts is that alkyl groups depress the base-catalyzed enolization rate of ketones. Furthermore, striking differences are often observed during preparative experiments in acid- and base-catalyzed halogenation of the same ketone. Thus while methyl alkyl ketones undergo base-catalyzed iodination almost exclusively in the methyl group (iodoform reaction), acid-catalyzed halogenation generally takes place in the alkyl group.

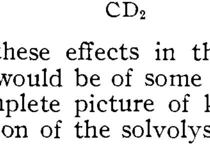


$$B{:}^{\ominus} + R_2CHCOR \longrightarrow BH + R_2C{=}\overset{O^{\ominus}}{C}R \quad \text{I}$$

$$\underset{\text{II}}{R_2CH\overset{OH}{C}R^{\oplus}} \longrightarrow H^{\oplus} + R_2C{=}\overset{OH}{C}R$$

In contrast to the above theory of ketone enolization, Swain[2] has presented rather convincing evidence that both the acid- and base-catalyzed enolization of acetone are termolecular reactions involving a nucleophile and an electrophile. Swain analyzed the rather complete rate data on acetone iodination and showed quite clearly that these data were acceptably explained by a termolecular transition state for ketone enolization. Swain did not, however, attempt to present a complete picture of ketone enolization or to explain many of the facts which the Ingold school had utilized in developing their concepts.

In order to obtain a more detailed picture of ketone enolization, it was decided to determine the secondary deuterium isotope effects in the enolization of cyclopentyl-2,2,5,5-d_4 phenyl ketone (IIIa) and cyclohexyl-2,2,6,6-d_4 phenyl ketone (IIIb). Recently the use of secondary hydrogen isotope effects has been developed as a potentially useful tool for studying hyperconjugation so the knowledge of these effects in the above systems conceivably would be of some value in formulating a more complete picture of ketone enolization. In examination of the solvolysis of secondary chlorosulfites Lewis and Boozer initially observed that when β-deuterium was substituted for β-protium, these esters solvolyzed at a considerably slower rate.[3] The transition state for this reaction has a great deal of carbonium ion character so the observed isotope effect is best explained by weakening



IIIa, $n = 2$; IIIb, $n = 3$

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[1] C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell Univ. Press, Ithaca, N. Y., 1953, pp. 557–559; see also R. P. Bell and P. Jones, *J. Chem. Soc.*, 88 (1953).

[2] C. G. Swain, THIS JOURNAL, **72**, 4578 (1950).

[3] E. S. Lewis and C. E. Boozer, *ibid.*, **76**, 791 (1954).