All of the experiments on thermal denaturation reported here were carried out in $H_2O$ solution. The deuterio-phycocyanin was isolated and stored in $H_2O$. The deuterio-phycocyanin therefore probably has hydrogen at all the exchangeable positions. A sample of deuterio-phycocyanin dialyzed against $H_2O$ for several days was denatured, dried in vacuum, and burned. The water of combustion showed about 83% $D_2O$. This result is in agreement with the observation that about 20% of the hydrogen in many proteins is exchangeable. Even though it is recognized that some exchangeable hydrogen atoms may exchange only slowly, the great majority of the hydrogen bonding positions in $H_2O$ solutions of deuterio-phycocyanin can be expected to be occupied by hydrogen in view of the protracted exposure of the protein to $H_2O$. It would appear, therefore, that the observed differences in transition temperature are not primarily a consequence of a change in hydrogen bonding or of ionic bonds as well. Rather, the differences must be associated with differences in side chain interactions.[25]

Phycocyanin appears to possess an about average number of non-polar amino acids (Table III). It is hard to avoid the conclusion that it is the replacement of hydrogen by deuterium in the non-polar amino acids and the consequent differences in apolar or hydrophobic bond interactions that are primarily responsible for the present observations. Until the configurational stability of deuterio-phycocyanin is studied by other means, and until these studies are extended to other deuteriated proteins, it is premature to attempt an assessment of the relation between hydrogen and deuterium apolar bonds. It would appear, however, that fully deuteriated proteins present a unique experimental situation in which attention can be focused directly on the role of non-polar amino acids in protein configuration.

**Acknowledgments.**—We wish to express our thanks to Messrs. Jon Palmer and Norman Solliday who provided very capable technical assistance in securing the amino acid analyses.

(25) W. Kauzmann, "Advances in Protein Chemistry," Vol. XIV, Academic Press, Inc., New York, N. Y., 1959, p. 33 et seq.; I. Klotz, *Brookhaven Symp. Biol.*, **13**, 25 (1960).

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[CONTRIBUTION FROM THE CHEMISTRY DEPARTMENT, BROOKHAVEN NATIONAL LABORATORY, UPTON, N. Y.]

# The Secondary α-Deuterium Isotope Effect in the Thermal Decomposition of α-Phenylethylazo-2-propane[1,2]

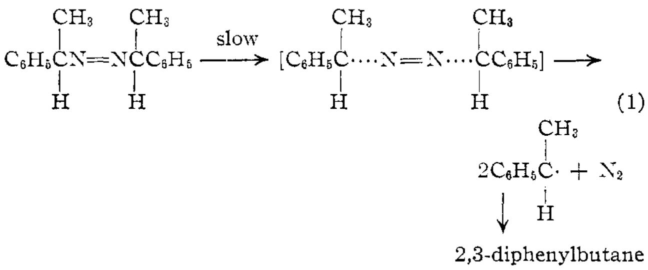
BY STANLEY SELTZER

RECEIVED JUNE 6, 1962

α-Phenylethyl-α-*d*-azo-2-propane (II) and α-phenylethylazo-2-propane-2-*d* (III) were prepared. The rates of decomposition of these compounds, in addition to the natural compound I, were measured and compared. The isotope effects are $k_{I}/k_{II} = 1.15$ and $k_{I}/k_{III} = 1.04$. The conclusions drawn from these isotope effects are: (1) both carbon–nitrogen bonds break simultaneously, and (2) the α-phenylethyl carbon–nitrogen bond is stretched considerably more than the 2-propyl carbon–nitrogen bond in going from the starting state to the transition state. An apparent contradiction of two rules predicting the structure of the transition state is discussed.

## Introduction

Recently, it has been reported from this Laboratory, that the secondary α-deuterium isotope effect in the radical decomposition of azo-bis-α-phenylethane-α-α′-$d_2$ in ethylbenzene at 105° is $k_H/k_D = 1.27$.[3] Since this effect is approximately twice as large as those encountered in other "unimolecular" reactions, it was taken as evidence for both carbon–nitrogen bonds breaking simultaneously in the transition state of the rate-controlling step (eq. 1).



$$\mathrm{C_6H_5\underset{H}{\overset{CH_3}{C}}N{=}N\underset{H}{\overset{CH_3}{C}}C_6H_5} \xrightarrow{\text{slow}} [\mathrm{C_6H_5\underset{H}{\overset{CH_3}{C}}\cdots N{=}N\cdots \underset{H}{\overset{CH_3}{C}}C_6H_5}] \longrightarrow \mathrm{2C_6H_5\underset{H}{\overset{CH_3}{C}}\cdot + N_2} \quad (1)$$

$$\downarrow$$

2,3-diphenylbutane

The interpretation of this isotope effect rests upon the comparison of its magnitude (observed in a radical reaction) with those encountered in reactions approaching S<sub></sub>N1 character. The Arrhenius activation energies, measured in the solvolytic reactions, are a little more than half the 32.6 kcal./mole activation energy observed[4] for the decomposition of azo-bis-α-phenylethane. If a stepwise mechanism of decomposition is assumed, with the first step being rate controlling, then the high activation energy for this endothermic step suggests a transition state closely resembling products[5] (*i.e.*, α-phenylethyl and α-phenylethylazo radicals). A less likely interpretation of the large isotope effect follows from this assumption: that it represents a greater reorganization of atoms (hence a greater change in the α-hydrogen vibrational frequencies) in going from the reactant state to the transition state in the case of the azo compound decomposition than in the solvolytic reactions. In other words, the observed effect, $k_H/k_D = 1.27$, would be due to only one of the two D atoms in azo-bis-α-phenylethane-α,α′-$d_2$. (This interpretation is referred to in the Discussion as case A, while the previous interpretation is designated as case B.) This alternate possibility was investigated by measuring the two secondary α-deuterium isotope effects in the unsymmetrical azo compound α-phenylethylazo-2-propane.

## Experimental

**α-Phenylethylhydrazine** (I).—Acetophenone azine, m.p. 120.4–122.1°, 10.3 g., in 200 ml. of ethyl acetate in the presence of 1.7 g. of 5% Pd–C (Baker Catalyst Co.) was hydrogenated at room temperature at a pressure of approximately 14 p.s.i. The reduction was stopped after one mole equivalent of $H_2$ was added. After filtering and evaporating the solvent, the yellow oil was added to a solution of 9 g. of oxalic acid dihydrate in 30 ml. of absolute alcohol plus 30 ml. of ether. This solution was stirred for 20 hours at room temperature. The white solid, α-phenylethylhydrazinium oxalate, was filtered off, washed, and dried; m.p. 170.2–170.8° dec., lit. 172°[6]; yield 6.1 g., 62%.

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(1) Presented in part at the American Chemical Society Meeting, Chicago, Ill., September, 1961.

(2) Research performed under the auspices of the U. S. Atomic Energy Commission.

(3) S. Seltzer, *J. Am. Chem. Soc.*, **83**, 2625 (1961).

(4) S. G. Cohen, S. J. Groszos and D. B. Sparrow, *ibid.*, **72**, 3947 (1950).

(5) G. S. Hammond, *ibid.*, **77**, 334 (1955).

(6) C. G. Overberger and A. V. DiGiulio, *ibid.*, **80**, 6562 (1958).

The remainder of the synthesis was carried out according to the method of Overberger and DiGiulio.[6] The azo compound I distilled at 53° (0.8 mm.), $n^{25}_D$ 1.4918 (lit.[6] 1.4917).

**α-Phenylethyl-α-*d*-azoisopropane** (II).—$LiAlD_4$, 2.93 g. from Metal Hydrides, Inc. (98.8% D), was added to a solution of 73.3 g. of acetophenone azine in 1.5 l. of absolute ether. The solution was refluxed in an atmosphere of $N_2$ for about 48 hours whereupon the color changed from yellow to bright orange. At the end of this period the solution was neutralized with about 10 ml. of water and the yellow color reappeared. A 10% KOH solution was added to dissolve the inorganic solid and the two layers were separated. After drying the ether layer over KOH, the solvent was distilled through a 12-inch Vigreux column. The hydrolysis of the acetophenone α-phenylethyl-α-*d*-hydrazone was carried out as described above yielding 33.6 g. of crude salt, m.p. 162–163° dec. The remainder of the synthesis was the same as previously described.[6] Distillation of the azo compound was accomplished with a 12-inch platinum spiral vacuum-jacketed column; b.p. 47–48° (0.29 mm.), $n^{25}_D$ 1.4919.

**α-Phenylethylazoisopropane-2-*d*** (III).—Acetone α-phenylethylhydrazone, b.p. 69° (0.31 mm.), $n^{25}_D$ 1.5292, 8.78 g. in 40 ml. of ether, was added dropwise over a period of 1.5 hours to a refluxing slurry of 2.76 g. of $LiAlD_4$ (98.8% D) in 500 ml. of ether. The mixture was stirred and refluxed in an atmosphere of nitrogen for 19 hours while the solution turned yellow-green and then to yellow. Water was added to decompose any unreacted hydride. KOH solution was used to solubilize the inorganic precipitate. After drying, the ether layer was distilled yielding an oil, b.p. 68° (0.9 mm.), $n^{25}_D$ 1.5049, yield 7.25 g. (81%).

The above hydrazine was oxidized with HgO as described previously[7] yielding the azo compound, b.p. 54° (0.7 mm.), $n^{25}_D$ 1.4921, 4.74 g. (54%).

**Deuterium analysis** was performed as previously described.[7]

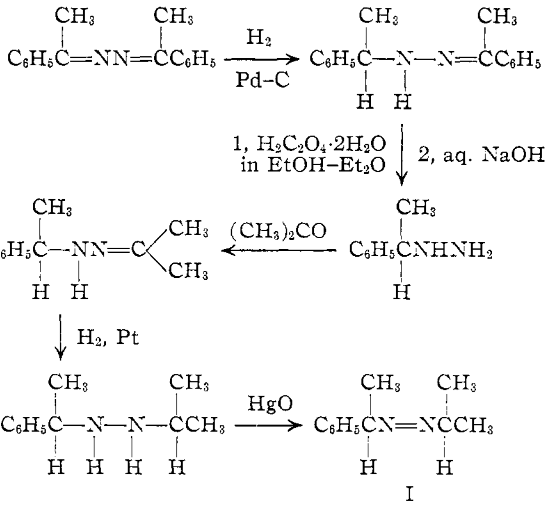
N.m.r. spectra of the three compounds were recorded by Varian Associates. The peaks appeared in the order: aromatic-hydrogen, benzylic-hydrogen (quartet), isopropyl-tertiary hydrogen (septet) and methyl-hydrogen (complex). The position of labeling was verified by the disappearance of the quartet for compound II and the disappearance of the septet for compound III. The spectra also indicated more than 98% deuteriation in each position.

**Kinetic measurements** were carried out by measuring the rate of nitrogen evolution in an all glass system at 143.20 ± 0.05°. The reaction flask, essentially a 100-ml. cylinder, had creases in its wall to ensure efficient mixing. A glass-encased magnetic stirring bar was sealed inside the flask. Three narrow tubes emerged from the flask at 120-degree intervals; two were capillary. One capillary tube was sealed to the manometer with Apiezon W wax; the other was used to admit the sample after temperature equilibration of the solution. The third tube was used for introducing the solvent. Fifty ml. of a 0.13 *M* solution of benzoquinone in distilled diphenyl ether was pipetted into the flask. A vigorous stream of nitrogen was passed through the solution for 15 minutes. It was then placed in the thermostated bath and the solution stirred by a rotating magnet from above while a slow stream of nitrogen passed through. After about 15 minutes the system (flask and manometer) was evacuated to about 150 mm. When the mercury level in the manometer came to equilibrium, the sample was admitted by turning a stopcock located between one of the capillary tubes and a small reservoir containing the sample (1–2 mmoles) in diphenyl ether and nitrogen. One mmole of $N_2$ produced a change of approximately 170 mm. in the height of the mercury column which was measured with a cathetometer. The manometer was so designed that a movement in one arm of 2500 mm. would produce a change of only 1 mm. in the other arm. The volume outside the bath amounted to about 20% of the total, but this was jacketed with running tap water to maintain a constant temperature.

## Results

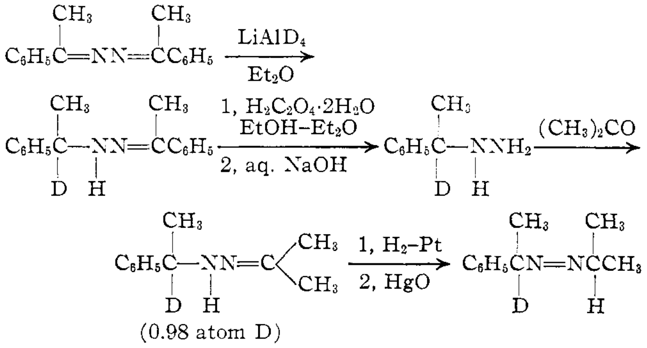
The three different isotopically substituted α-phenylethylazo-2-propane molecules were synthesized according to the schemes outlined in Charts I, II and III. The method, leading to specifically labeled materials, resembled that used by Overberger and DiGuilio[6] for the synthesis of the parent compound. Confirmation of the extent and position of deuterium labeling was obtained from the n.m.r. spectra (see Experimental). In addition, the labeled compounds were analyzed for deuterium by mass spectral analysis of the hydrogen derived from the burned compounds; these results are shown in the charts.

CHART I



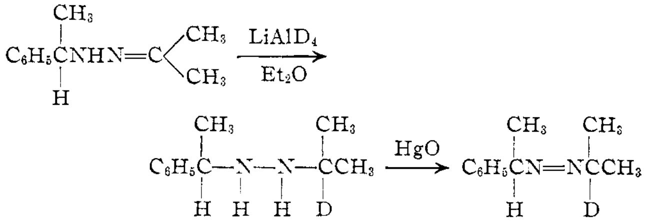
$n^{25}_D$ 1.4918, $n^{25}_D$ 1.4917 (Overberger and DiGiulio)

CHART II



II (0.98 atom D) $n^{25}_D$ 1.4919

CHART III



(III) (1.01 atoms D), $n^{25}_D$ 1.4921

The kinetics of decomposition of each compound were determined at 143.20 ± 0.05° in diphenyl ether several times by measuring the rate of nitrogen evolution in an all-glass system. Overberger and DiGuilio found that the presence of approximately 0.1 *M* benzoquinone reduced the 10% excess gas formed during reaction to zero, within the error of the experiment. The excess gas in this case is probably propane or propylene formed by hydrogen abstraction or loss from the propyl radicals produced in the thermolysis of α-phenylethylazo-2-propane which do not dimerize or add to the α-phenylethyl radicals. Benzoquinone

TABLE I

FIRST-ORDER RATE CONSTANTS FOR THE THERMAL DECOMPOSITION OF α-PHENYLETHYLAZO-2-PROPANE[a]

| | α-Phenylethylazo-2-propane $k_I \times 10^4$, sec.$^{-1}$ | α-Phenylethyl-α-*d*-azo-2-propane $k_{II} \times 10^4$, sec.$^{-1}$ | α-Phenylethylazo-2-propane-2-*d* $k_{III} \times 10^4$, sec.$^{-1}$ |
|---|---|---|---|
| | 1.49$_5$ | 1.32$_3$ | 1.45$_0$ |
| | 1.51$_4$ | 1.29$_3$ | 1.46$_3$ |
| | 1.50$_2$ | 1.29$_9$ | 1.45$_4$ |
| | | 1.32$_6$ | 1.44$_1$ |
| Av. | 1.50$_4$ ± 0.007 | 1.31$_0$ ± 0.01$_4$ | 1.45$_2$ ± 0.007 |

$k_I/k_{II} = 1.14_8 \pm 0.01_2$, $k_I/k_{III} = 1.03_6 \pm 0.007$

[a] In diphenyl ether–benzoquinone solution at 143.20 ± 0.05°.

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(7) S. Seltzer, *J. Am. Chem. Soc.*, **83**, 1861 (1961).

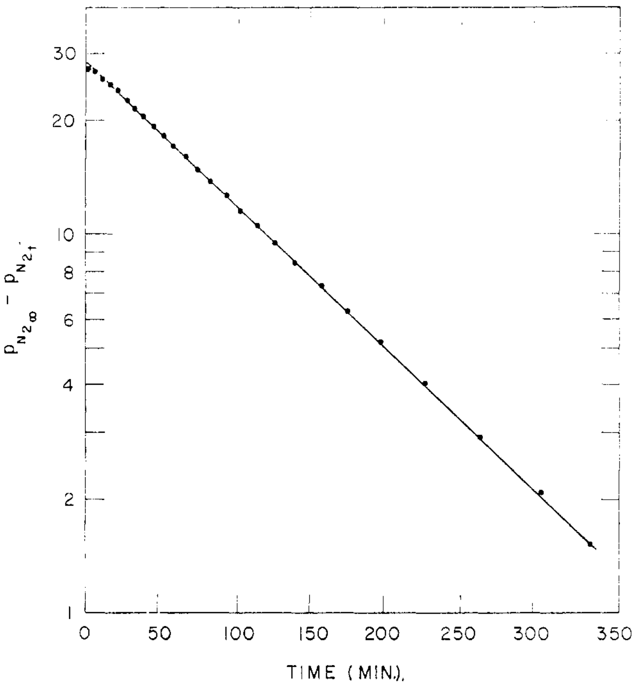


Fig. 1.—Sample kinetic plot of the decomposition of α-phenylethylazo-2-propane-2-*d* in diphenyl ether–benzoquinone solution at 143.20°.

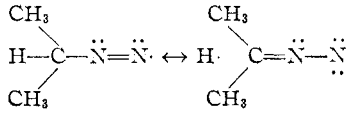
serves as a scavenger for these radicals thereby preventing the formation of a volatile gas. It has already been shown[3] that the fate of the α-phenylethyl radical, formed from azo-bis-α-phenylethane in ethylbenzene, is dimerization rather than hydrogen abstraction. The same is probably true when the solvent is diphenyl ether. Abstraction of hydrogen atoms from the substrate by propyl radicals would have the net result of increasing the rate of carbon–nitrogen bond breaking with an over-all kinetic isotope effect different from that of the reaction under study. For this reason benzoquinone was used as a radical scavenger. A sample first-order plot is shown in Fig. 1. The individual rate constants obtained by an IBM 704 computer[3] from the least-squares treatment of 20 to 30 points for each run, are shown in Table I.

## Discussion

If the different mechanisms of thermolytic cleavage of dialkyl azo compounds are considered together with the two opposing interpretations of the large secondary α-deuterium isotope effect discussed in the Introduction, then three sets of data are possible. Case A: If it is assumed that azo-bis-α-phenylethane decomposes in two discrete steps and that the large isotope effect can be correlated with greater progress along the reaction coördinate than in the case of the solvolytic reactions, then here, too, in the case of α-phenylethylazo-2-propane, we would predict $k_I/k_{II} \cong 1.3$. On the other hand, if the large isotope effect had been correctly interpreted as representing a simultaneous two-bond rupture, then there are two possible cases for the decomposition of α-phenylethylazo-2-propane. Case B-1: One should observe $k_I/k_{II} \cong k_I/k_{III} \cong 1.15$ if both bonds were breaking simultaneously. Case B-2: If a stepwise scission were occurring during the decomposition, however, the expected set of isotope effects would be $k_I/k_{II} \cong 1.15$ and $k_I/k_{III} \cong 1.0$ or $k_I/k_{II} \cong 1.0$ and $k_I/k_{III} \cong 1.15$, depending on which bond breaks first.

The experimental data falls somewhere between cases B-1 and B-2. The isotope effect, $k_I/k_{II} = 1.15$, confirms the previous interpretation and makes the alternate interpretation (case A) untenable. It further establishes that the benzylic-carbon–nitrogen bond is breaking in the rate-determining step. The secondary α-deuterium isotope effect, $k_H/k_D = 1.04$, at the other carbon–nitrogen bond is low and can be explained best by only one of three possible interpretations.

If it is assumed for the moment that there is a stepwise bond breaking in the decomposition of α-phenylethylazo-2-propane, with the benzylic-carbon–nitrogen bond breaking first, then we might inquire about the secondary isotope effect in any hyperconjugative stabilization of the incipient 2-propylazo radical of the type



Shiner,[8] Lewis[9] and others[10] have measured secondary β-deuterium effects and have correlated the data with the ability of a molecule or activated complex to hyperconjugate. In most cases where the deuterium atom is bonded to a carbon atom truly alpha to the reaction site (*i.e.*, in a position to stabilize the adjacent carbonium ion by no-bond resonance) the secondary isotope effect is large, $k_H/k_D = 1.1$ to 1.2 per D atom. If, however, this stabilization is to be transmitted through a conjugated system as it would have to be in this reaction, the observed isotope effects are close to being non-existent; $k_H/k_D = 1.00$.[8,11] The kinetic isotope effect, $k_H/k_D = 1.04$, is too large to be correlated with any hyperconjugative stabilization of a transient isopropylazo radical.

Kinetic analysis of the series first-order reaction

$$\mathrm{RN{=}NR'} \xrightarrow{k_1} \mathrm{RN{=}N\cdot} + \mathrm{\cdot R'} \qquad (2)$$

$$\mathrm{RN{=}N\cdot} \xrightarrow{k_2} \mathrm{R\cdot} + \mathrm{N_2} \qquad (3)$$

leads to the equation[12]

$$(p_{N_2\infty} - p_{N_2})/p_{N_2\infty} = \frac{k_2e^{-k_1t} - k_1e^{-k_2t}}{k_2 - k_1} \qquad (4)$$

If $k_1 >> k_2$ or $k_2 >> k_1$, eq. 4 reduces to a first-order equation. If, however, the logarithm of the quantity on the left is plotted *versus t*, for cases where one rate constant is not very much greater than the other, an apparent "induction period" will be observed with the remainder of the plot resembling good first-order kinetics. A small induction period was originally observed by Overberger and DiGiulio[13]; in the present study it was found to be $t_{ind}/t_{1/2} \leqslant 0.2$, when the kinetics were plotted as a first-order reaction (see Fig. 1). If an unsymmetrical azo compound, substituted with deuterium at only one α-carbon atom, actually decomposed in two separate steps, with a "normal" 15% isotope effect for either $k_1$ or $k_2$, then the observed effect would only be 15% in the limiting case; rather, it would be some value between zero and 15% depending on the ratio of $k_1/k_2$. This is shown more clearly in Fig. 2 where a series first-order reaction is plotted as a first-order reaction for two different ratios of $k_1/k_2$, 0.1 and 0.5, respectively. In each of these two hypothetical cases a 15% isotope effect is introduced into the faster second step and the observed

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[8] V. J. Shiner, Jr., *Tetrahedron*, **5**, 243 (1959); *J. Am. Chem. Soc.*, **82**, 2655 (1960).

[9] E. S. Lewis, *ibid.*, **5**, 143 (1959).

[10] For a recent review see R. E. Weston, Jr., *Ann. Rev. Nucl. Sci.*, **11**, 439 (1961).

[11] C. G. Swain, T. E. C. Knee and A. J. Kresge, *J. Am. Chem. Soc.*, **79**, 505 (1957).

[12] A. A. Frost and R. G. Pearson, "Kinetics and Mechanisms," John Wiley and Sons, Inc., New York, N. Y., 1953, p. 154.

[13] C. G. Overberger and A. V. DiGiulio, *J. Am. Chem. Soc.*, **81**, 2154 (1959).

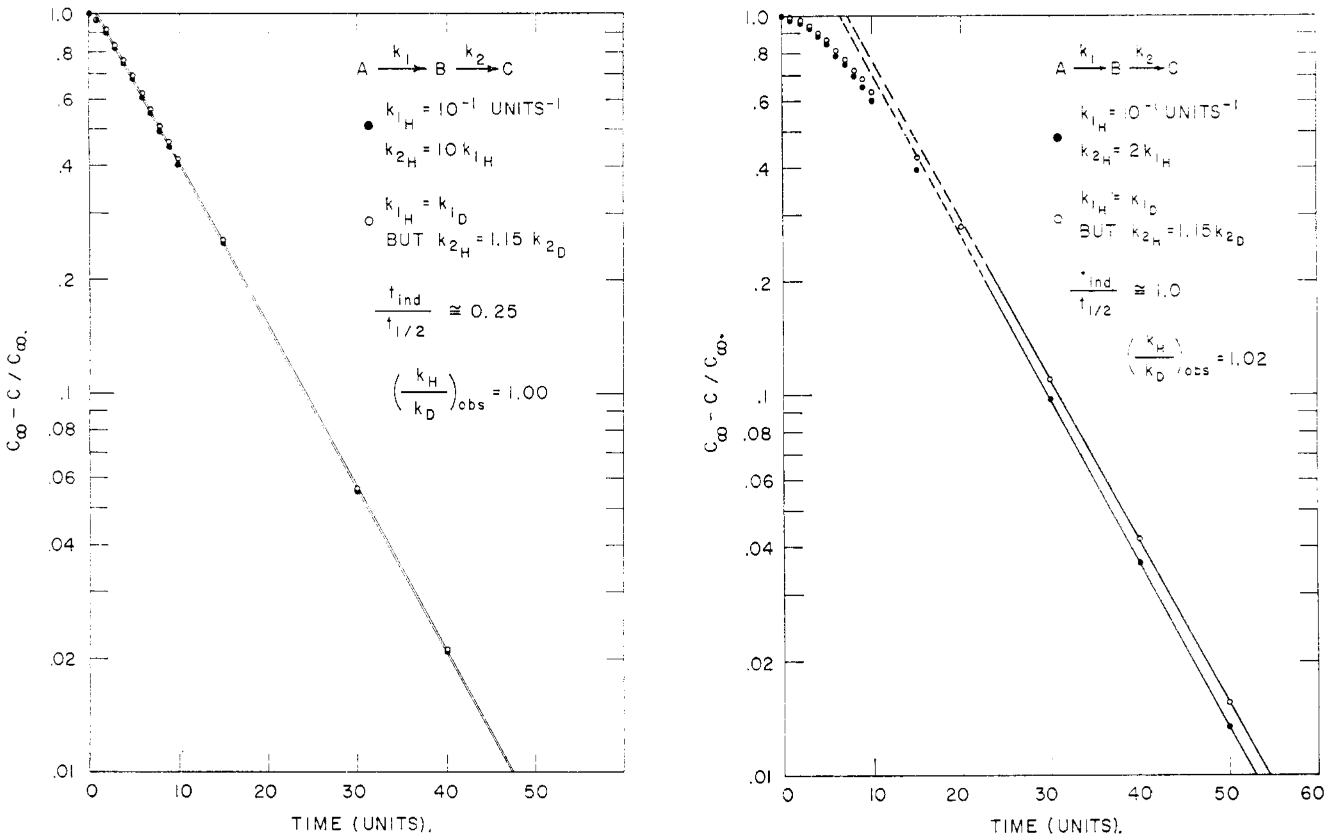
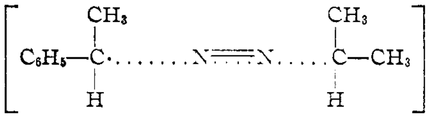


Fig. 2.—A hypothetical series first-order reaction of deuteriated and non-deuteriated molecules, plotted as a first-order reaction: ●, natural compound; ○, monodeuteriated compound; A (left figure), $k_1/k_2 = 0.1$; B (right figure), $k_1/k_2 = 0.5$.

isotope effect is determined graphically. For the case where $k_1/k_2 = 0.1$ (Fig. 2A), a deuterium isotope effect of 15% in $k_2$ produces no observable over-all isotope effect, while if $k_1/k_2 = 0.5$ (Fig. 2b) an over-all 2% effect is observed for similar conditions. This is not surprising for it was similar reasoning that led Westheimer and Nicolaides[14] to determine the rate-controlling step in the chromic acid oxidation of 2-propanol. From this treatment another parameter, $t_{ind}/t_{1/2}$, is obtained. When $k_1/k_2 = 0.1$, $t_{ind}/t_{1/2} \cong 0.25$ while if $k_1/k_2 = 0.5$, $t_{ind}/t_{1/2} \cong 1.0$. Longer induction periods are found as $k_1/k_2$ increases except for large values of $k_1/k_2$ where they once again decrease. Therefore in order to observe a 4% isotope effect from a 15% effect in $k_2$, ratios of $k_1/k_2 \cong 2$ and $t_{ind}/t_{1/2} \cong 1$ would be characteristic for this kinetic scheme. This cannot be the case in the decomposition of α-phenylethylazo-2-propane because the experimental induction period is much shorter than the calculated period; both carbon–nitrogen bonds must be breaking simultaneously. The explanation for the small induction period must be found elsewhere.[15]

It has been proposed previously[7,16] that the difference between the observed secondary α-deuterium isotope effect in "unimolecular" decompositions and the theoretical value calculated for a complete change from starting state to a fully formed tricoördinated carbon atom or ion is some measure of the attainment, in the transition state, of a completely broken bond between the leaving group and the carbon atom. The effect, $k_I/k_{II} = 1.15$, would then represent the α-phenylethyl-carbon–nitrogen bond as being stretched an amount comparable to that found in some SN1 reactions and approximately equal to the stretch of each α-phenylethyl-carbon–nitrogen bond in the decomposition of azo-bis-α-phenylethane. The isotope effect, $k_I/k_{III} = 1.04$, on the other hand, represents a much smaller stretching of the 2-propyl-carbon–nitrogen bond. The transition state is then probably pictured[17] as



$$\left[ C_6H_5-\overset{\displaystyle CH_3}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}\cdot\cdots\cdots N{=\!=}N\cdots\cdots\overset{\displaystyle CH_3}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-CH_3 \right]$$

which is not unexpected in view of the greater ability of phenyl *versus* methyl in its ability in delocalizing a free electron[19] and thus allowing the attainment of greater radical character in the α-phenylethyl group in the transition state.

**Activation Energies and Progress Along the Reaction Coördinate.**—Hammond's postulate[5] has allowed greater definition in predicting whether a species in the transition state resembles more the reactants or products. From his postulate one can reason that a reactant is a good model for the transition state if the reaction step is exothermic and of low activation energy while the opposite is more likely if a high activation energy is encountered in an endothermic step. By an extension of this postulate, two similar reactants undergoing the same endothermic reaction can be com-

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[14] F. H. Westheimer and N. Nicolaides, *J. Am. Chem. Soc.*, **71**, 25 (1949).

[15] Cohen, *et al.*,[4] have suggested that an induction period during the decomposition of another azo compound was due to traces of oxygen. It might also be caused by a preliminary *cis–trans* conversion which would show no deuterium isotope effect.

[16] A. Streitwieser, Jr., R. H. Jagow, R. C. Fahey and S. Suzuki, *J. Am. Chem. Soc.*, **80** 2326 (1958).

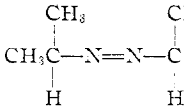
[17] The pictorial representation is actually exaggerated to indicate which of the two bonds is stretched the greater amount. Bond extensions in transition state have been calculated,[18] from pressure effects on reaction rates, to be 10–25% greater than in the starting state.

[18] A. H. Ewald, *Disc. Faraday Soc.*, **22**, 138 (1956); S. Benson, "Chemical Kinetics," McGraw-Hill Book Co., Inc., New York, N. Y., 1960, p. 517; "Tables of Interatomic Distances and Configuration in Molecules and Ions," Special Publication No. 11, The Chemical Society, London, 1958, pp. 8, 138.

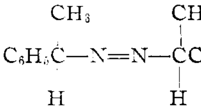
[19] C. Walling, "Free Radicals in Solution" John Wiley and Sons, Inc., New York, N. Y., 1957, pp. 50–51.

pared; the transition state with the higher activation energy would resemble its products more closely than would the transition state of lower activation energy resemble its products. Consideration of the magnitude of the secondary $\alpha$-deuterium isotope effect in these reactions presents an opposite conclusion.

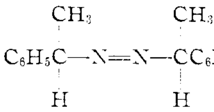
The Arrhenius activation energies in the thermal decomposition of azoisopropane[20] (A), $\alpha$-phenylethylazo-2-propane (B) and azo-bis-$\alpha$-phenylethane (C) are 40.9, 36.5 and 32.6 kcal./mole, respectively.


$\mathrm{CH_3\overset{CH_3}{\underset{H}{C}}{-}N{=}N{-}\overset{CH_3}{\underset{H}{C}}CH_3}$

A


$\mathrm{C_6H_5\overset{CH_3}{\underset{H}{C}}{-}N{=}N{-}\overset{CH_3}{\underset{H}{C}}CH_3}$

B


$\mathrm{C_6H_5\overset{CH_3}{\underset{H}{C}}{-}N{=}N{-}\overset{CH_3}{\underset{H}{C}}C_6H_5}$

C

Since there is very little or no resonance interaction of the CN=NC bonds with the groups bonded to carbon in any of these molecules,[21] it would appear that, as far as these bonds are concerned, on an energy of activation–reaction coördinate trace, all three molecules would be at the same energy level in their starting states. If the reaction coördinate is taken as an average of the extension in the two carbon–nitrogen bonds, the prediction[5] can be made that in the decomposition of azoisopropane, the transition state resembles more the products of this reaction step than does the corresponding transition state resemble its products in the decomposition of azo-bis-$\alpha$-phenylethane. The unsymmetrical compound would fall somewhere in between. This can then be taken to mean that of the three compounds, azoisopropane would show the greatest and azo-bis-$\alpha$-phenylethane the least carbon–nitrogen bond stretching in the transition state.

If the relationship of magnitude of the secondary $\alpha$-deuterium isotope effect (*i.e.*, the change in the $\alpha$-hydrogen force constant while reaching the transition state) to the degree of bond breaking is valid, one would place the transition state of C further along the reaction coördinate than that for B (*i.e.*, the transition state in the decomposition of azo-bis-$\alpha$-phenylethane resembles more its products than does the transition state of $\alpha$-phenylethylazo-2-propane resemble its corresponding products. The relative positioning of the transition state of A will have to await further measurements. Therefore, it would appear that the conclusions drawn from these measurements are in opposition to Hammond's postulate.

Very recently, Swain and Thornton[23] have proposed a new rule to allow a determination of the relative extents of bond breaking or making in the transition state from a consideration of the relative electronic nature of the reactants. Very briefly, the rule predicts that bonds, which are present in the reactant and absent in the product (bond-breaking), or absent in the reactant and present in the product (bond-making), will be progressively lengthened in the transition state as the electron-donating capacity of substituents is increased. It is necessary for the substituent's atomic orbitals to overlap with the *reacting orbitals* to permit this electrical effect to be transmitted to the reacting bonds. Application to the decomposition of azo-bis-$\alpha$-phenylethane and $\alpha$-phenylethylazo-2-propane would predict longer carbon–nitrogen bonds for C than for B in their transition states which is in agreement with the interpretation of the secondary $\alpha$-deuterium isotope effects in the decomposition of these molecules. It would appear from this rule, however, that the effect of substituents on one end of the C—N=N—C system would be transmitted to the other end and thus make impossible the distinction of an unsymmetrical transition state as found in the decomposition of B.

From a two nuclei–two electron model which neglects electronic repulsions, it was pointed out[23] that the effect of supplying electrons to bonds undergoing rupture is not only to lengthen them but also to raise the activation energy needed to move the nuclei and their respective electronic configurations apart. From the greater ability of phenyl than methyl to donate electrons in conjugative interaction, the predicted relative order of activation energies for the three azo compounds would be $A < B < C$; this is opposite to experimental observation. The activation energies are here only a measure of the difficulty of carrying out the process of stretching the two carbon–nitrogen bonds and shortening the nitrogen–nitrogen distance in the transition state of these three compounds. That there is no specific solvation effects to reverse the predicted order of activation energies, as might be the case in the hydrolysis of cumyl chlorides,[23] is shown by the almost identical rates of decomposition of a similar compound, azobisisobutyronitrile in very different solvents.[24] Therefore neither an extension of Hammond's postulate nor the rule proposed by Swain and Thornton appear to predict all the experimental observations in the decomposition of these three compounds.

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(20) H. C. Ramsperger, *J. Am. Chem. Soc.*, **50**, 714 (1928).

(21) The electronic absorption spectra of the azo linkage of these three compounds are very similar: azoisopropane,[22] $\lambda_{max}$ 356, log $\epsilon$ 1.25; $\alpha$-phenylethylazo-2-propane,[6] $\lambda_{max}$ 354, log $\epsilon$ 1.54; azo-bis-$\alpha$-phenylethane,[3] $\lambda_{max}$ 356, log $\epsilon$ 1.68.

(22) B. W. Langley, B. Lythgoe and L. S. Rayner, *J. Chem. Soc.*, 4191 (1952).

(23) C. G. Swain and E. R. Thornton, *Tetrahedron Letters*, **No. 6**, 211 (1961); *J. Am. Chem. Soc.*, **84**, 817 (1962).

(24) Reference 19, p. 512.