

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_D^{25} 1.4918 (lit.⁶ 1.4917).

α -Phenylethyl- α -*d*-azoisopropane (II).—LiAlD₄, 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 N₂ 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_D^{25} 1.4919.

α -Phenylethylazoisopropane-2-*d* (III).—Acetone α -phenylethylhydrazone, b.p. 69° (0.31 mm.), n_D^{25} 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 LiAlD₄ (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_D^{25} 1.5049, yield 7.25 g. (81%).

The above hydrazine was oxidized with HgO as described previously⁷ yielding the azo compound, b.p. 54° (0.7 mm.), n_D^{25} 1.4921, 4.74 g. (54%).

Deuterium analysis was performed as previously described.⁷

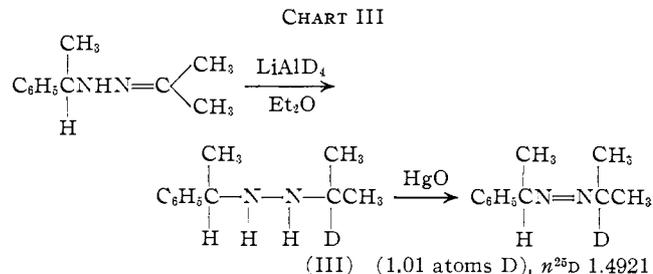
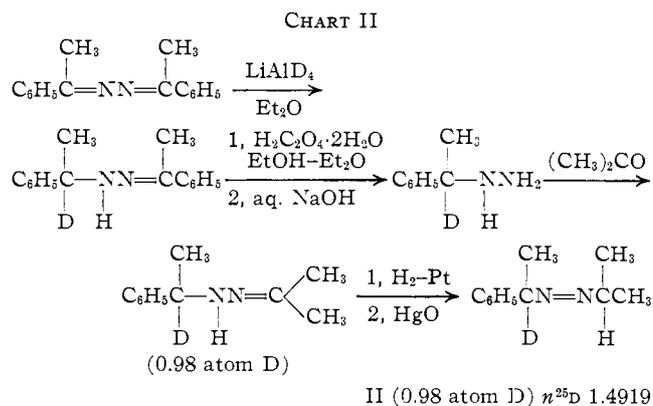
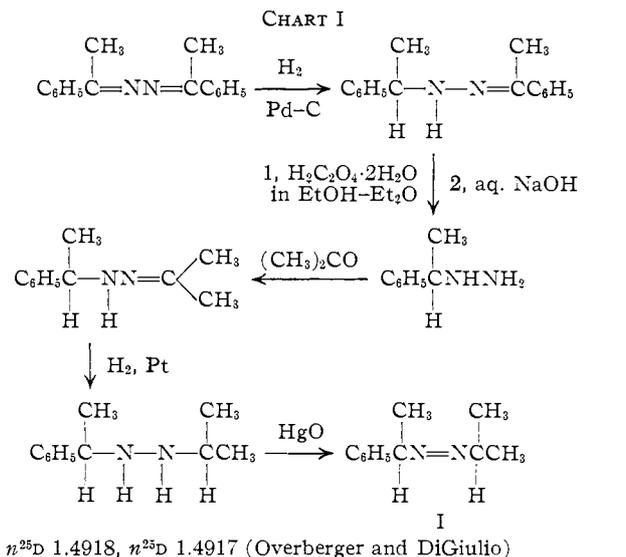
N.m.r. spectra of the three compounds were recorded by Varian Associates. The peaks appeared in the order: aromatic-hydrogen, benzylic-hydrogen (quartet), isopropyl-tertiary hydrogen (septet) and methyl-hydrogen (complex). The position of labeling was verified by the disappearance of the quartet for compound II and the disappearance of the septet for compound III. The spectra also indicated more than 98% deuteration 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 N₂ 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 DiGiulio⁶ 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.

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 DiGiulio 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 -PHENYLETHYL-AZO-2-PROPANE^a

α -Phenylethylazo-2-propane	α -Phenylethyl- α - <i>d</i> -azo-2-propane	α -Phenylethylazo-2-propane-2- <i>d</i>
$k_I \times 10^4, \text{sec.}^{-1}$	$k_{II} \times 10^4, \text{sec.}^{-1}$	$k_{III} \times 10^4, \text{sec.}^{-1}$
1.495	1.323	1.450
1.514	1.293	1.463
1.502	1.299	1.454
	1.326	1.441
Av. 1.504 ± 0.007	1.310 ± 0.014	1.452 ± 0.007

$$k_I/k_{II} = 1.148 \pm 0.012, k_I/k_{III} = 1.036 \pm 0.007$$

^a In diphenyl ether-benzoquinone solution at 143.20 ± 0.05°.

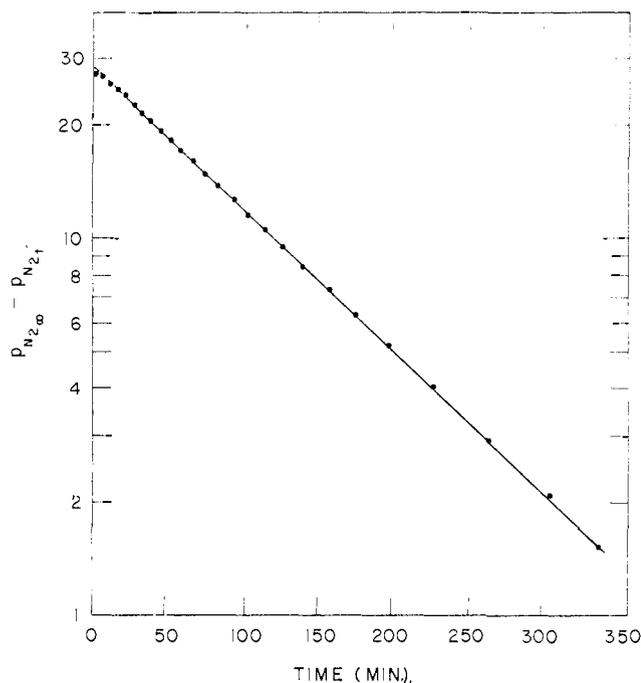


Fig. 1.—Sample kinetic plot of the decomposition of α -phenylethylazo-2-propane-2-*d* in diphenyl ether–benzoquinone solution at 143.20°.

serves as a scavenger for these radicals thereby preventing the formation of a volatile gas. It has already been shown³ 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 computer³ from the least-squares treatment of 20 to 30 points for each run, are shown in Table I.

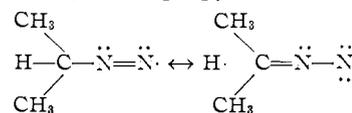
Discussion

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 coordinate 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

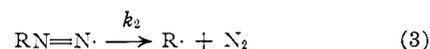
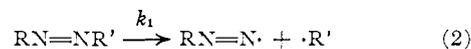
alternate interpretation (case A) untenable. It further establishes that the benzylic-carbon–nitrogen bond is breaking in the rate-determining step. The secondary α -deuterium isotope effect, $k_H/k_D = 1.04$, at the other carbon–nitrogen bond is low and can be explained best by only one of three possible 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 Lewis⁹ and others¹⁰ 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



leads to the equation¹²

$$(\text{P}_{\text{N}_2\infty} - \text{P}_{\text{N}_2,t})/\text{P}_{\text{N}_2\infty} = \frac{k_2 e^{-k_2 t} - k_1 e^{-k_1 t}}{k_2 - k_1} \quad (4)$$

If $k_1 \gg k_2$ or $k_2 \gg k_1$, 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 DiGiulio¹³; in the present study it was found to be $t_{\text{ind}}/t_{1/2} \leq 0.2$, 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

(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).

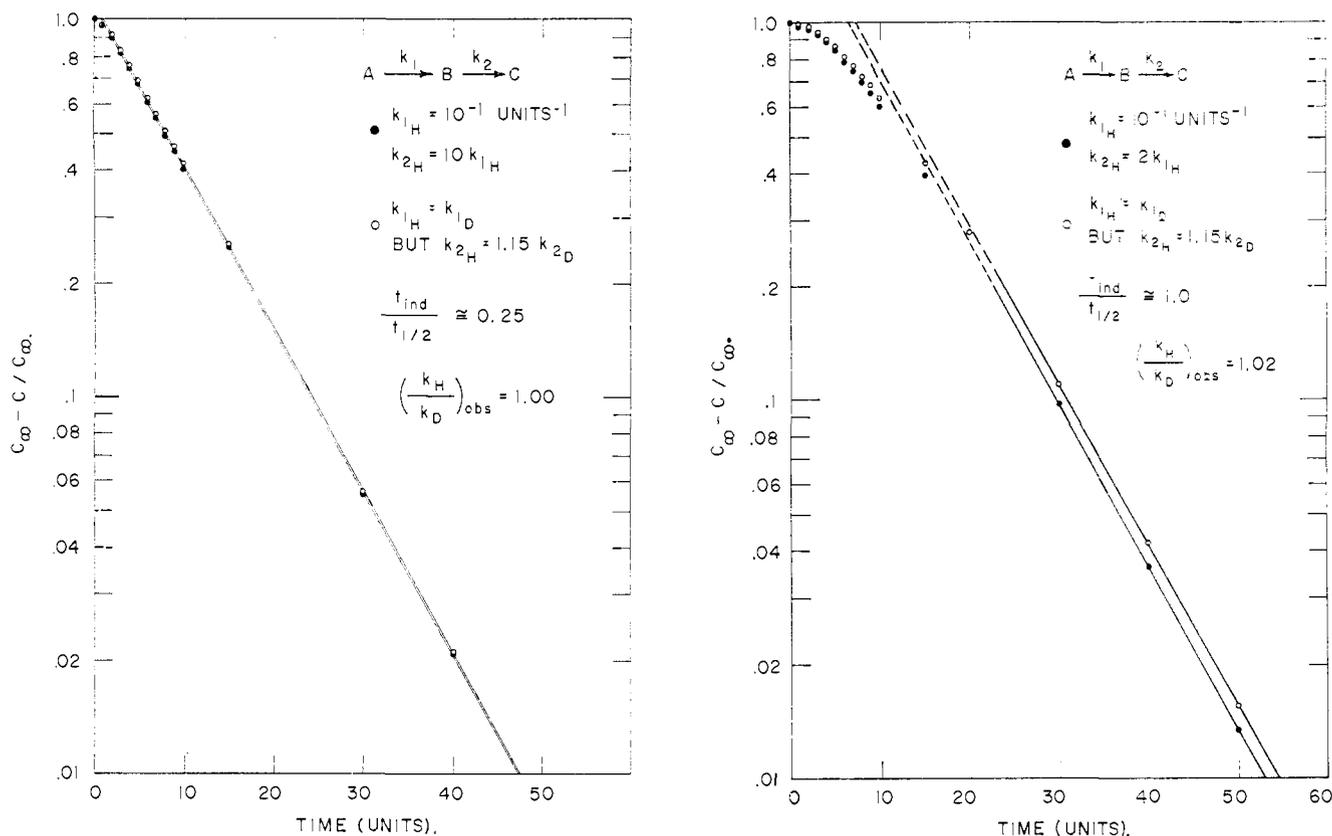


Fig. 2.—A hypothetical series first-order reaction of deuteriated and non-deuteriated molecules, plotted as a first-order reaction: ●, natural compound; ○, monodeuteriated compound; A (left figure), $k_1/k_2 = 0.1$; B (right figure), $k_1/k_2 = 0.5$.

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 Nicolaides¹⁴ 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 tricoordinated 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 S_N1 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 pictured¹⁷ as



which is not unexpected in view of the greater ability of phenyl *versus* methyl in its ability in delocalizing a free electron¹⁹ 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 postulate⁵ 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-

(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.

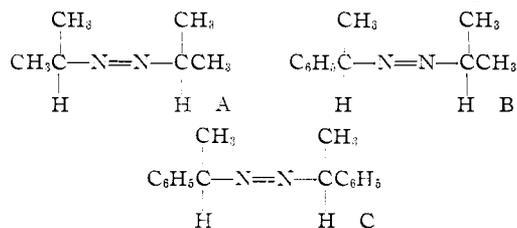
(14) F. H. Westheimer and N. Nicolaides, *J. Am. Chem. Soc.*, **71**, 25 (1949).
 (15) Cohen, *et al.*,⁴ have suggested that an induction period during the decomposition of another azo compound was due to traces of oxygen. It might also be caused by a preliminary *cis-trans* conversion which would show no deuterium isotope effect.

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

(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 α -deuterium isotope effect in these reactions presents an opposite conclusion.

The Arrhenius activation energies in the thermal decomposition of azoisopropane²⁰ (A), α -phenylethylazo-2-propane (B) and azo-bis- α -phenylethane (C) are 40.9, 36.5 and 32.6 kcal./mole, respectively.



Since there is very little or no resonance interaction of the $\text{CN}=\text{NC}$ 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 coordinate trace, all three molecules would be at the same energy level in their starting states. If the reaction coordinate is taken as an average of the extension in the two carbon-nitrogen bonds, the prediction⁵ 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- α -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- α -phenylethane the least carbon-nitrogen bond stretching in the transition state.

If the relationship of magnitude of the secondary α -deuterium isotope effect (*i.e.*, the change in the α -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 coordinate than that for B (*i.e.*, the transition state in the decomposition of azo-bis- α -phenylethane resembles more its products than does the transition state of α -phenylethylazo-2-propane resemble its corresponding products. The relative positioning of the transition state of A will have to await further measurements.

(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 λ_{max} 356, $\log \epsilon$ 1.25; α -phenylethylazo-2-propane,⁶ λ_{max} 354, $\log \epsilon$ 1.54; azo-bis- α -phenylethane,³ λ_{max} 356, $\log \epsilon$ 1.68.

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

Therefore, it would appear that the conclusions drawn from these measurements are in opposition to Hammond's postulate.

Very recently, Swain and Thornton²³ 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- α -phenylethane and α -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 α -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 $\text{C}-\text{N}=\text{N}-\text{C}$ 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 out²³ 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.

(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.