

saturated aqueous potassium carbonate in a graduated cylinder and was identified as methyl chloride by infrared spectrophotometry.<sup>16</sup>

(16) R. H. Pierson, A. N. Fletcher, and E. St. Clair Gantz, *Anal. Chem.*, **28**, 1218 (1956).

In a separate experiment 2-methoxypyrimidine (5.51 g., 0.050 mole) was dissolved in 2 *N* hydrochloric acid (30 ml., 0.060 mole) and hydrolyzed as above. The volume of methyl chloride collected (230 ml. at STP) represented a 21% yield based on 2-methoxypyrimidine.

## The Mechanism of the Diels–Alder Reaction of 2-Methylfuran with Maleic Anhydride<sup>1,2</sup>

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Five different deuterated isomers of the *exo* adduct (I) formed from 2-methylfuran and maleic anhydride were synthesized and their rates for retro Diels–Alder reaction in isooctane at about 50° were determined. From the nature of these secondary  $\alpha$ - and  $\beta$ -deuterium isotope effects, we conclude that the two bonds formed between diene and dieneophile are ruptured in a concerted process in the reverse Diels–Alder reaction. The n.m.r. spectra of these compounds are discussed.

### Introduction

The question of the detailed mechanism of the Diels–Alder reaction<sup>3</sup> still commands attention.<sup>2,4,5</sup> Whether the two new bonds are formed in two separate steps or in one concerted step with equal or unequal bond making is of primary importance. Several new approaches have been used to distinguish between these possibilities but disagreement still exists.<sup>4,5</sup> A new method which appears to be well suited for the study of the relative timing of the formation of two bonds is the secondary  $\alpha$ -deuterium isotope effect. The subject of this paper deals with the  $\alpha$ - and  $\beta$ -deuterium effects in the decomposition of the Diels–Alder adduct derived from 2-methylfuran and maleic anhydride. From the results, we conclude that the two new bonds must form simultaneously.

### Experimental

2-Methylfuran, supplied by Eastman Kodak, was redistilled before use, b.p. 64°,  $n^{25}_D$  1.4300.

(1) (a) Research performed under the auspices of the U. S. Atomic Energy Commission. (b) The majority of the work described herein was presented at the Gordon Conference on "The Chemistry and Physics of Isotopes," New Hampton, N. H., July 1962.

(2) For preliminary reports of this work see (a) S. Seltzer, *Tetrahedron Letters*, No. 11, 457 (1962); (b) *J. Am. Chem. Soc.*, **85**, 1360 (1963).

(3) M. C. Kloetzel, *Org. Reactions*, **4**, 1 (1948).

(4) For pertinent literature references see (a) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, pp. 711–721; (b) R. B. Woodward and T. J. Katz, *Tetrahedron*, **5**, 70 (1959).

(5) (a) C. Walling and J. Peisach, *J. Am. Chem. Soc.*, **80**, 5819 (1958); (b) J. A. Berson, R. D. Reynolds, and W. M. Jones, *ibid.*, **78**, 6049 (1956); (c) J. A. Berson, A. Remanick, and W. A. Mueller, *ibid.*, **82**, 5501 (1960); (d) J. A. Berson and W. A. Mueller, *ibid.*, **83**, 4940 (1961); **83**, 4947 (1961); (e) J. Sauer, D. Lang, and A. Mielert, *Angew. Chem.*, **74**, 352 (1962); (f) R. P. Lutz and J. D. Roberts, *J. Am. Chem. Soc.*, **83**, 2198 (1961); (g) M. J. Goldstein and G. L. Thayer, Jr., *ibid.*, **85**, 2673 (1963).

Maleic anhydride, supplied by Pfanstiehl was sublimed before use.

2-Methylfuran-5-*d*. 2-Methylfuran was converted to 2-chloromercuri-5-methylfuran.<sup>6</sup> The 2-chloromercuri-5-methylfuran, 47.5 g., was suspended in a 50–50 mixture (w./w.) of EtOD–D<sub>2</sub>O (*vide infra*) which was approximately 1 *M* in D<sub>2</sub>SO<sub>4</sub>. An amount of NaCl, equivalent to the quantity of sulfuric acid, was added and the mixture was refluxed for 0.5 hr. The fraction boiling up to 70° was collected, dissolved in ether, and dried over MgSO<sub>4</sub>. The ether was fractionated through a 12-in. platinum spiral column until about 25% of the original volume remained. This was chromatographed, in 3–4-ml. portions, on a 12-ft. Ucon column at 70° to yield 4.5 g. of 2-methylfuran-5-*d*.

EtOD–D<sub>2</sub>O solution was prepared by refluxing 177 g. (1.5 moles) of E.K.C. diethyl carbonate in 140 ml. of D<sub>2</sub>O plus 11 ml. of approximately 19 *N* D<sub>2</sub>SO<sub>4</sub>. After 72 hr. only one phase was visible; after another 24 hr. only 3% of the original ester was unhydrolyzed as determined by infrared.<sup>7</sup>

Maleic anhydride-*d*<sub>2</sub> was prepared as described previously.<sup>8</sup>

Maleic Anhydride-*d*<sub>1</sub>. Bromomaleic anhydride, prepared according to previously published methods,<sup>9</sup> was dissolved in ethyl ether to which a slight excess of D<sub>2</sub>O was added. The ether was evaporated off and the bromomaleic acid-*d*<sub>2</sub> was recrystallized from nitromethane, m.p. 127–128° (lit.<sup>9b</sup> m.p. 128°). *Anal.* Calcd. for Br: 40.32. Found: 39.53. The electrolysis was carried out with a preconditioned lead cathode (175 cm.<sup>2</sup>) and a wire mesh platinum anode. The anode compartment was essentially a fine fritted cylinder that was suspended inside the main cylindrical compartment. A typical reduction was carried out with the catholyte containing 17.3 g. (0.088 mole) of bromomaleic acid-*d*<sub>2</sub>, 100 ml. of D<sub>2</sub>O, and 15 ml. of 10.7 *M* NaOD. The anolyte consisted of 20 ml. of 10.7 *M* NaOD. The main compartment was stirred while

(6) H. Gilman and G. F. Wright, *ibid.*, **55**, 3302 (1933).

(7) R. N. Jones, D. A. Ramsay, D. S. Keir, and K. Dobriner, *ibid.*, **74**, 80 (1952).

(8) S. Seltzer, *ibid.*, **83**, 1861 (1961).

(9) (a) A. Michael, *J. prakt. Chem.*, **52**, 289 (1895); (b) C. K. Ingold, *J. Chem. Soc.*, 121, 1306 (1922); (c) S. Cristol, *J. Am. Chem. Soc.*, **74**, 5025 (1952).

cooled externally with running tap water. A current of 2 amps was passed for the required time after which the catholyte was acidified with  $D_2SO_4$  solution. The acidified solution was continuously extracted with ether for about 20 hr. In this way, the aqueous layer could be reused after distillation for another reduction. The ether was evaporated off leaving behind a mixture of maleic-*d* and fumaric-*d* acid- $d_2$ . After drying under vacuum, the mixture was sublimed with  $P_2O_5$ , as described previously,<sup>8</sup> yielding 6.9 g. of crude anhydride. Several batches of crude anhydride were combined and distilled through a 12-inch platinum spiral column. The middle cut was collected, m.p. 50–52.4°.

**2-Methyl- $d_3$ -furan.** To a slurry of 3.68 g. (0.0875 mole) of  $LiAlD_4$  (Metal Hydrides Co.) in 250 ml. of ether was added a solution of 24.5 g. (0.175 mole) of ethyl furoate (b.p. 99° at 25 mm.) in about 100 ml. of ether. The solution was refluxed for 1 hr. after the addition was completed and then allowed to stand overnight. The excess hydride was decomposed by the addition of water followed by NaOH solution. The layers were separated and the ether extract was dried and distilled to yield an oil, b.p. 92° at 30 mm. The distillate was dissolved in ether and an equal weight of distilled  $PBr_3$  in ether was added dropwise with stirring while the flask was cooled.<sup>10</sup> An insoluble black oil developed. After several hours the ether layer was decanted and added dropwise to a slurry of  $LiAlD_4$  in ether. The mixture was stirred and refluxed for 2 hr. and then hydrolyzed with excess NaOH solution. The ether layer was washed several times with water, dried, and distilled yielding a yellow-brown oil. The oil was chromatographed on a Ucon column at 65°, yielding 0.36 g. An infrared spectrum indicated the methyl group to be approximately 90% deuterated.

A more suitable synthesis might have been realized by the reaction of  $CD_3I$  and 2-furyllithium since a 37% yield was obtained with natural methyl iodide. 2-Furyllithium was prepared from 15.3 g. (0.22 mole) of furan and 0.25 mole of butyllithium as described<sup>11</sup> and added to a solution of 28 g. (0.2 mole) of  $CH_3I$  in about 50 ml. of ether. The mixture was refluxed for 8 hr. and the reaction was quenched with water. The ether layer was washed with water until the water was clear and neutral. The ether was dried and the solution was distilled. The fraction boiling between 63.5 and 65°,  $n_D^{25} 1.4270$ , was collected, yielding 5.8 g.

**4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-*exo*-5,6-dicarboxylic Acid Anhydride (I).** All the natural and deuterated adducts were prepared in the same manner. Purified maleic anhydride was dissolved in a minimum amount of ether and an equivalent quantity of 2-methylfuran was added. A yellow color immediately appeared. The solution was generally allowed to stand at room temperature for about 1 day and at about -20° for another day. The crystals were filtered off and recrystallized from ethyl acetate, m.p. 75–76° dec. (lit.<sup>12</sup> m.p. 80, 84°),  $\epsilon_{211\text{ m}\mu} = 1170$  (isooctane, at  $t = 0$ ),<sup>13</sup> **4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-5,6- $d_2$ -*exo*-5,6-dicarboxylic acid anhydride (II)**

(10) (a) J. E. Zanetti, and J. T. Bashour, *J. Am. Chem. Soc.*, **61**, 2249 (1939); (b) R. B. Woodward, *ibid.*, **62**, 1478 (1940).

(11) (a) W. E. Truce and E. Wellisch, *ibid.*, **74**, 5177 (1952); (b) R. A. Benkeser and R. B. Currie, *ibid.*, **70**, 1780 (1948).

(12) (a) K. Alder and K. H. Backendorf, *Ann.*, **535**, 101 (1938); (b) I. J. Rinkes, *Rec. trav. chim.*, **50**, 1127 (1931).

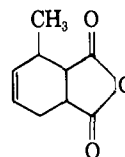
had m.p. 76–77° dec. **4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-1-*d*-*exo*-5,6-dicarboxylic acid anhydride (III)** had m.p. 74–75° dec.

**4-Methyl- $d_3$ -7-oxabicyclo[2.2.1]-2-heptene-*exo*-5,6-dicarboxylic Acid Anhydride (VI).** Because of the small quantity, the adduct was purified by sublimation, m.p. 74–75° dec. **4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-5,6- $d_1$ -*exo*-5,6-dicarboxylic acid anhydride (IV + V)** had m.p. 75.5–76.5° dec.

**Kinetics** were measured at  $49.80 \pm 0.05^\circ$  in isooctane solution (1% ether). Stock solutions of the adduct, approximately  $1.8\text{--}4.5 \times 10^{-4} M$  in isooctane (5% ether), were prepared and stored in the freezer. Before use the solution was allowed to warm to room temperature; aliquots were taken and diluted to make final concentrations of  $10^{-5}$  to  $9 \times 10^{-5} M$  in adduct. The optical density at 211  $m\mu$  was measured on a Beckman DU spectrophotometer as a function of time while the cell temperature was held constant by Beckman dual thermospacers through which water from a constant-temperature bath was circulated. Initial readings up to the first 12 min. were discarded due to the lag in temperature equilibration between the quartz cell and the thermostated compartment. In each run, approximately 30 points were taken as far as 10 half-lives and the data were used to solve for the nonlinear least-squares solution of the first-order rate equation by an IBM 704 or 7094 computer.<sup>14</sup>

**Decomposition of 4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-5,6- $d_1$ -*exo*-5,6-dicarboxylic Acid Anhydride.** In a typical run, 4.3 g. of monodeuterated adduct was dissolved in 75 ml. of Matheson Spectrograde dioxane at room temperature. An aliquot was taken and diluted to an approximately  $10^{-5} M$  solution in 30% dioxane-isooctane. At zero time, the 75-ml. solution of adduct in dioxane was added to 175 ml. of previously thermostated isooctane. At the same time the  $10^{-5} M$  solution was placed in the thermostated compartment of the Beckman DU and the kinetics were measured. Both of the solutions were thermostated at the same temperature,  $49.60 \pm 0.05^\circ$ . After the appropriate time (80–90% reaction) the flask was removed and the reaction was quenched by cooling the solution in ice. The solvent and 2-methylfuran were removed on a rotary evaporator while keeping the solution below 25°. Approximately 1 hr. was required for evaporation. Maleic anhydride- $d_1$  and any remaining solvent were removed when the residue was sublimed at 0.3 mm. while the residue was held at -10°. The residue was then taken up in  $CH_2Cl_2$ , filtered, and the adduct was precipitated with  $CCl_4$ . It was recrystallized further with ethyl acetate, m.p. 72.4–73.2°. In one run, the residue from sublimation at 0.3 mm. was sublimed under high vacuum at room temperature without prior recrystallization, m.p. 76–77°. The recovered adduct was dissolved in a minimum of acetone and the n.m.r.

(13) Z. W. Wicks, O. W. Daly, and H. Lack, *J. Org. Chem.*, **12**, 715 (1947), report  $\epsilon_{211} = 1265$  for



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

peaks from protons in positions 5 and 6 were integrated about 18 times going in both directions on a 50-c.p.s.-wide chart. The same procedure was repeated for the starting material.

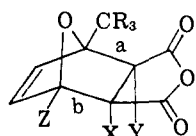
**$C^{14}$ -Exchange Experiments.** Maleic anhydride-2,3- $C^{14}$  (Merck Ltd., 0.1 mc., 8.5 mg.) was washed with ether into a vacuum sublimator. To this was added 2.04 g. of natural maleic anhydride and the ether was evaporated with a slow stream of  $N_2$ . The solid was sublimated under vacuum. The measured activity of the sublimate was  $85.7 \pm 1.0 \mu\mu\text{C}/\text{mg.}$  of carbon.

In a typical run the decomposition of 4.2 g. of natural adduct in the presence of 0.147 g. of maleic anhydride-2,3- $C^{14}$  in 30% dioxane-isooctane was carried out in the same manner as the studies involving the decomposition of 4-methyl-7-oxabicyclo[2.2.1]-2-heptene-5,6- $d_1$ -*exo*-5,6-dicarboxylic acid anhydride.

*N.m.r.* spectra were taken on a Varian A-60 spectrometer in  $\text{CHCl}_3$  with the solvent being used as the internal standard.

## Results

The six different deuterated isomers (II-VI) of the *exo*-Diels-Alder adduct of 2-methylfuran and maleic



- I, X = Y = Z = R = H  
 II, X = Y = D; Z = R = H  
 III, X = Y = R = H; Z = D  
 IV, X = D; Y = Z = R = H  
 V, Y = D; X = Z = R = H  
 VI, X = Y = Z = H; R = D

anhydride were prepared according to the schemes outlined in Chart I. The *n.m.r.* spectrum of the natural compound I is shown in Figure 1. The spectra

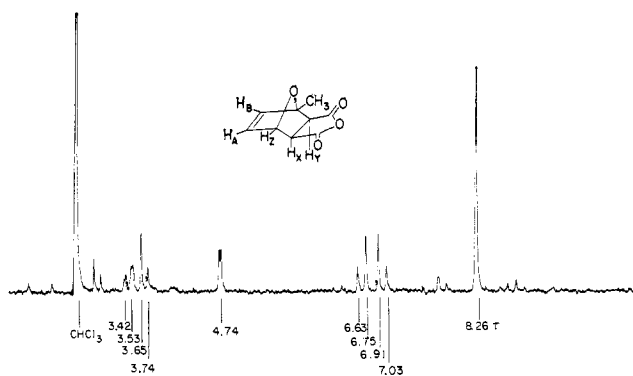


Figure 1. *N.m.r.* spectrum of 4-methyl-7-oxabicyclo[2.2.1]-2-heptene-*exo*-5,6-dicarboxylic acid anhydride (I).

of compounds II-VI were entirely consistent with the structures assigned from the methods of synthesis. Each of the isomers were analyzed for deuterium as previously described<sup>8</sup>; these are listed in Table I.

The rates of reversion to addends of the mono-deuterated (III), dideuterated (II), trideuterated (VI), and natural (I) adducts were measured spectrophotometrically by observing the increase of optical density at  $211 \mu\mu$  for solutions having initial concentrations of

Table I. Deuterium Analyses of Isomeric Adducts

Compd.	Atoms of D	
	Conversion to hydrogen	Infrared
II	$1.89 \pm 0.004$	
III	$0.94 \pm 0.03$	
IV, V	$1.09 \pm 0.02^a$	$1.13 \pm 0.05^b$
VI	$2.86 \pm 0.03$	

<sup>a</sup> The precursor, maleic anhydride- $d_1$ , was analyzed in this case.  
<sup>b</sup> The intensities of the C-H bending vibration in known concentrations of natural and monodeuterated maleic anhydride were compared.

adduct varying from  $4 \times 10^{-5}$  to  $9 \times 10^{-5} M$  in isooctane (1% ether). Both 2-methylfuran and maleic anhydride absorb strongly at this wave length<sup>15</sup>; the starting material absorbs very weakly. Kinetics of decomposition were followed to 10 half-lives with about 30 points taken for each run. In each case the data were processed by an IBM 704 or 7094 computer to obtain the nonlinear least-squares solution of the first-order rate equation.<sup>14</sup> The runs were carried out in two groups as shown in Tables II and III. Within

Table II. First-Order Rate Constants for the Formation of 2-Methylfuran and Maleic Anhydride from 4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-*exo*-5,6-dicarboxylic Acid Anhydride<sup>a</sup>

Natural, I <sup>b</sup>	Dideuterated, II <sup>b</sup>	Monodeuterated, III <sup>b</sup>
4.15	3.67	3.88
4.08	3.51	3.84
4.25	3.61	3.85
4.14	3.58	3.83
4.10	3.60	3.89
Av. $4.14 \pm 0.04$	$3.59 \pm 0.04$	$3.86 \pm 0.02$
$k_I/k_{II} = 1.15 \pm 0.01$	$k_I/k_{III} = 1.07 \pm 0.01$	
$k_I/k_{III} = 1.16 \pm 0.01$	$k_I/k_{III} = 1.08 \pm 0.01$	
(corr.)	(corr.)	

<sup>a</sup>  $t = 49.80 \pm 0.05^\circ$  in isooctane containing 1% ether. <sup>b</sup>  $k \times 10^4$ ,  $\text{sec.}^{-1}$ .

Table III. First-Order Rate Constants for the Formation of 2-Methylfuran and Maleic Anhydride from 4-Methyl-7-oxabicyclo[2.2.1]-2-heptene-*exo*-5,6-dicarboxylic Acid Anhydride<sup>a</sup>

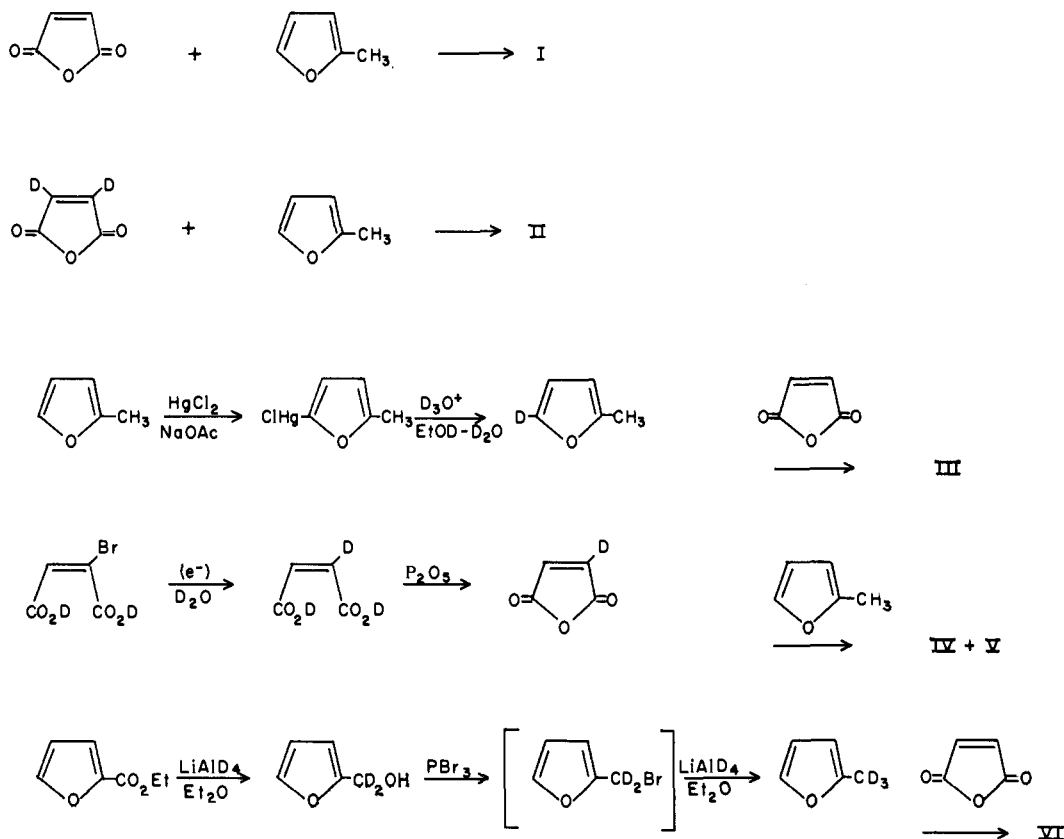
Natural, I <sup>b</sup>	Trideuterated, VI <sup>b</sup>
4.02	3.84
3.99	3.80
4.02	3.92
4.07	3.94
4.01	3.86
3.96	3.88
	3.95
	3.88
Av. $4.01 \pm 0.03$	$3.88 \pm 0.04$
	$k_I/k_{VI} = 1.03 \pm 0.01$

<sup>a</sup>  $t = 49.60 \pm 0.05^\circ$ , in isooctane containing 1% ether. <sup>b</sup>  $k \times 10^4$ ,  $\text{sec.}^{-1}$ .

each group a staggered order was adopted to minimize any error due to long term variation of the bath temperature. The observed isotope effects when corrected

(15) H. L. Rice, *J. Am. Chem. Soc.*, **74**, 3193 (1952).

Chart I



for complete deuteration at the sites under study are  $k_I/k_{II} = 1.16$ ,  $k_I/k_{III} = 1.08$ , and  $k_I/k_{VI} = 1.03$ .

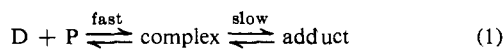
In addition to the direct determination of the secondary isotope effect when deuterium is substituted for hydrogen at the *endo*-5,6-positions (I vs. II), the relative secondary  $\alpha$ -deuterium isotope effect of the *endo*-5- $d_1$  (IV) vs. the *endo*-6- $d_1$  (V) adducts was determined by n.m.r. The observed relative effect is  $k_{IV}/k_V = 1.00$ .

### Discussion

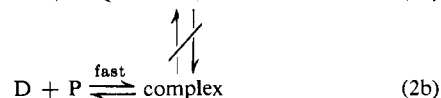
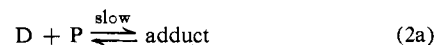
Reactions involving "unimolecular" homolytic or heterolytic cleavage of a C-X bond generally show about a 12% decrease in the rate of bond breaking, at about 100° when deuterium is substituted for hydrogen on the carbon atom originally bonded to the leaving group.<sup>14,16</sup> The effect appears to be due to the loss in zero-point energy in the H-C leaving group bending mode in going from reactant to transition state.<sup>16a,17</sup> These secondary  $\alpha$ -deuterium effects have been used successfully in the relative timing of each of the two C-N bond ruptures in the thermal decomposition of dialkylazo compounds<sup>14,18</sup> and in the formation of two new bonds in the reaction of cyclohexene with diphenylketene.<sup>19</sup> The reasoning that is used is as follows. If  $\alpha$ -deuterium substitution decreases the rate of bond cleavage by about 12% at one reaction site,

then if there are two reaction sites in a molecule, each undergoing "unimolecular" type simultaneous cleavage, one should expect a *double isotope effect* when each reaction site has an  $\alpha$ -deuterium atom.<sup>20</sup> If on the other hand one of the two bonds breaks in a slow step followed by rupture of the second in a fast step then an effect of about 12% should be observed,<sup>21</sup> even though  $\alpha$ -deuterium is present at both reaction sites. Conversely, in a reaction where two new bonds are formed an inverse isotope effect of double magnitude should be expected if both bonds form simultaneously.

A problem that arises in the study of the mechanism is: in what direction should the reaction be followed? In reaction of a diene with a dienophile, a transitory color attributable to a diene-dienophile complex is often observed. Representative equilibrium constants for complexes of this type, but lacking the possibility of further reaction to form adduct, have been measured by Andrews and Keefer.<sup>22</sup> Such a complex can be involved in two different ways in the mechanism, *viz.*



or



where D and P are diene and dienophile, respectively. It should be pointed out that the complex may or may

(16) (a) A. Streitwieser, Jr., R. H. Jagow, R. C. Fahey, and S. Suzuki, *J. Am. Chem. Soc.*, **80**, 2326 (1958); (b) R. E. Weston, Jr., *Ann. Rev. Nucl. Sci.*, **11**, 439 (1961); (c) E. A. Halevi, "Progress in Physical Organic Chemistry," Vol. 1, Interscience Publishers, Inc., New York, N. Y., 1963, p. 109.

(17) M. Wolfsberg and M. J. Stern, *J. Pure Appl. Chem.*, **8**, 325 (1964); **8**, 225 (1964).

(18) (a) S. Seltzer, *J. Am. Chem. Soc.*, **85**, 14 (1963); (b) Abstracts, 146th National Meeting of the American Chemical Society, Denver, Colo., Jan. 1964, p. 4C.

(19) T. J. Katz and R. Dessau, *J. Am. Chem. Soc.*, **85**, 2172 (1963).

(20) Since these effects are mainly zero-point energy effects, the isotope effect should not be doubled but squared, *i.e.*,  $(1.12)^2 = 1.25$ .

(21) For a recent test of this semiempirical rule see A. A. Zavitsas and S. Seltzer, *J. Am. Chem. Soc.*, **86**, 1265 (1964); **86**, 3836 (1964).

(22) L. J. Andrews and R. M. Keefer, *ibid.*, **75**, 3776 (1953).

Table IV. N.m.r. Determination of  $k_{IV}/k_V$ 

[IV + V] <sub>0</sub> , M	[IV/V] <sub>0</sub> , <sup>a</sup> obsd.	% reaction	[IV/V] <sub>f</sub> , <sup>a</sup> obsd.	[IV/V] <sub>f</sub> /[IV/V] <sub>0</sub> <sup>b</sup> calcd. for	
				$k_{IV}/k_V$ = 1.00	$k_{IV}/k_V$ = 1.15
0.0796	1.01 ± 0.02	82	1.00 ± 0.04 <sup>c</sup>	1.00	1.25
0.0959	1.02 ± 0.06	81	1.00 ± 0.04	1.00	1.24
0.1132	1.00 ± 0.02	87	0.99 ± 0.04	1.00	1.31

<sup>a</sup> Each ratio is the average of 18 or more integrations. Errors are average deviations. <sup>b</sup> See ref. 23 for the calculation. <sup>c</sup> Remaining adduct purified by high vacuum sublimation.

not resemble the transition state between adduct and addends. Some support has been given to reaction proceeding by eq. 1<sup>3,5b</sup> but reaction by eq. 2 cannot be ruled out. If reaction occurs by eq. 2 and it is carried out in the direction of forming adduct, the observed isotope effect would be complicated by any contribution from an equilibrium (eq. 2b) isotope effect because of the preferential concentration of one of the isotopic molecules in the complex. The same is true if reaction occurred by eq. 1. If, however, the true reaction operates by eq. 2 and it is studied in the reverse direction, concentrations of starting state adduct can be low enough ( $10^{-4}$ – $10^{-5}$  M) to make eq. 2b unimportant to the over-all kinetics and to the observed isotope effects. The complex cannot be eliminated from the scheme if the mechanism is in fact represented by eq. 1, but a very low concentration of complex is ensured by a low initial concentration of adduct and thereby the complication of an equilibrium isotope effect is also removed. The observed effect in the reverse direction, by a mechanism represented in eq. 1, gives us information about the bonding changes in going from the adduct to the transition state located between the complex and adduct. On the chance that the reaction of maleic anhydride and 2-methylfuran proceeds by eq. 2, the decomposition rather than formation of the adduct was studied.

The adduct from maleic anhydride- $d_2$  was first chosen for study since the anhydride had been synthesized previously.<sup>8</sup> The isotope effect ( $k_I/k_{II} = 1.16 \pm 0.01$  at about 50°) was found for its decomposition in isooctane, an inert solvent. In the absence of other isotope effects for this system one would conclude from the foregoing discussion that this represents a secondary  $\alpha$ -effect for only a one-bond break, a or b in the slow step. Differentiation between a-rupture and b-rupture could be obtained by studying the  $\alpha$ -effect when Z = D in the adduct III. If b were breaking in the slow step an effect  $k_I/k_{III} = 1.16$  would be expected. If on the other hand the slow step involved rupture of a, an effect of 1.00 would be anticipated. The unexpected effect of  $k_I/k_{III} = 1.08 \pm 0.01$  was found. These results can be rationalized in three ways: (a) to completely disregard any stereo or electronic effects of a methyl group vs. a hydrogen atom by assuming that it were equally probable for either only a or b to break in the slow step followed by rupture of the second bond in a fast step,<sup>2a</sup> (b) that b breaks in a slow step followed by rapid a-rupture, and for some unknown reason the secondary  $\alpha$ -deuterium isotope effect at different ends of bond b are different, or (c) that the magnitude of the isotope effects generated in the decomposition of this bicyclo compound are not comparable to the average effects observed in the unimolecular decomposition of

acyclic compounds. Alternative c, it should be noted, can accommodate a *simultaneous* rupture of a and b by presuming that the average  $\alpha$ -effect equals 1.08 in this system. The only solid inference, however, that can be drawn from the first two experiments is that b ruptures half or all of the time in the slow step.

To distinguish between the alternate possibilities a and c on one hand and b on the other, the adducts IV and V were synthesized as an equimolar mixture. If this mixture is allowed to decompose to a large extent, the unreacted portion should still contain equimolar quantities of IV and V if either possibilities a or c were real.<sup>23</sup> While for mechanism b at 90% reaction, the unreacted 10% would contain a molar ratio IV/V = 1.30 if b ruptures in a slow step. This assumes a 15% decrease in the rate when deuterium is substituted at X but no effect when substituted at Y because a would be rupturing in a fast successive step.

Fortunately, the XY protons are observed as a simple AB quartet in the n.m.r. spectrum (*vide infra*) of the natural adduct (Figure 1). The quartet disappears in II, is unaltered in III, and results in collapse of the quartet to two singlets in a mixture of IV and V with each of the peaks representing one of the isomers. One then has a method of measuring the relative concentrations of IV and V by simply measuring the areas of the two peaks. The results in Table IV show that equal isotope effects operate when D is substituted at X or Y indicating that interpretation b is unreal. Furthermore, it should be pointed out that this conclusion does not rely on any previous knowledge of the magnitude of the effect to be expected.

To check that we were observing the true molar ratio in unreacted adduct after substantial decomposition, parallel experiments of decomposition of adduct in solutions containing maleic anhydride- $C^{14}$  were carried out to determine the maximum degree of return under the conditions of the previous experiment. As reported previously,<sup>2b</sup> the maximum quantity of returned adduct in the remaining starting material after about 78% decomposition is less than 20%.

If bonds a and b were to break in separate steps it would be expected that a and b form in separate steps, and if an effect of  $k_V/k_{IV} = 1.15$  is assumed for the decomposition of adduct, it might be expected that in the returned adduct the rate of formation of IV would be favored by 15% over V,<sup>24</sup> and independent of the extent of return.<sup>8,25</sup> Therefore, contamination by 20%

(23) J. Bigeleisen and M. Wolfsberg in "Advances in Chemical Physics," Vol. I, I. Prigogine, Ed., Interscience Publishers, Inc., New York, N. Y., 1958, p. 38.

(24) See however, D. E. Van Sickle, *Tetrahedron Letters*, No. 19, 687 (1961); *J. Am. Chem. Soc.*, **86**, 3091 (1964).

(25) The corrected expected  $[IV/V]_f$  for a two-step decomposition is  $0.20 [(IV/V)_{\text{returned}} \cong 1.15] + 0.80 [(IV/V)_{\text{unreacted}} \cong 1.30] = 1.27$ .

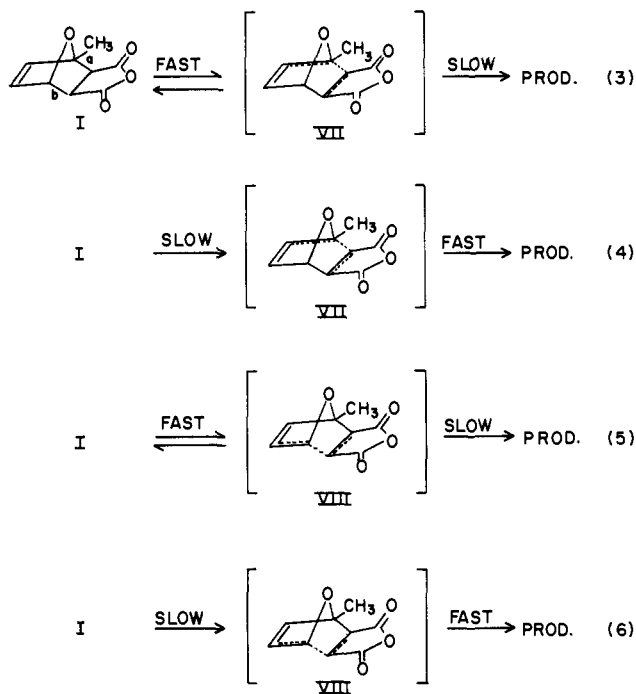
of returned adduct cannot substantially change the calculated ratio  $[IV/V]_f/[IV/V]_0$  from the values listed in the last column of Table IV.<sup>25</sup> As can be seen from the last three columns of Table IV, the ratio  $[IV/V]_f$  corresponds to a concerted rupture of a and b with equal amount of breaking of each bond at the transition state. These and the previous results also fit the less probable mechanism of two concurrent stepwise reactions occurring with equal over-all rates (reactions 3–6). To differentiate between the two mechanisms a and c, the isotope effect in the decomposition of the trideuteriomethyl adduct was measured.

Mainly from the work of Lewis<sup>26</sup> and Shiner<sup>27</sup> and their co-workers it is known that deuterium substitution on carbon,  $\beta$  to a leaving group, generally results in a secondary kinetic isotope effect with the  $\beta$ -deuterated isomer reacting some 10–20% more slowly in  $S_N1$  reactions. This has been explained by the decreased ability of deuterium to enter into hyperconjugative stabilization of the incipient carbonium ion in these reactions. Further substantiation has been found recently in the stereochemical requirements of these effects<sup>28</sup> and the finding that these  $\beta$ -effects are very small in bimolecular nucleophilic displacements where charge development on the  $\alpha$ -carbon atom is much smaller.<sup>29</sup> Undoubtedly, a factor in  $\beta$ -effects is that caused by relief of nonbonded interactions in the transition state<sup>30</sup> but this is probably a small contributor as shown by some recent studies.<sup>31</sup> Although it appears that hyperconjugative stabilization of radicals is less important than when carbonium ions are pro-

duced,<sup>32</sup> nevertheless, it too is significant enough to produce a  $\beta$ -effect of about 10% per deuterium atom in the benzylic-hydrogen abstraction of cumene.<sup>33</sup> From the nature of the causes of the  $\beta$ -effect, it would be expected that in other reactions, where a developing empty p-orbital overlaps with an adjacent incipient filled p-orbital, as in an E2 reaction,  $\beta$ -effects would be small because there is little requirement for hyperconjugative stabilization. From this we would conclude that substitution of deuterium in the methyl group of the adduct would produce a sizable effect if it were to decompose with polar or radical rupture of bond a but not b in a slow step (eq. 4) and probably a comparable equilibrium effect in a rapid rupture of a as in eq. 3; reaction by eq. 6 would be expected to produce no isotope effect other than that due to a pre-exponential mass effect.

If it were equally probable for a or b to break in a slow or fast step followed by rupture of the other bond in a fast or slow step, *i.e.*, (i) equations 3 and 5 or (ii) equations 4 and 6, or even (iii) equal amounts of reaction by equations 3, 4, 5, and 6, half of the molecules must pass through a stage, whether it be polar or radical, that would be expected to produce  $\beta$ -effects as large as those mentioned above. As can be seen from Table III the effect  $k_I/k_{VI} = 1.03$  (three atoms of D) is extremely small and inconsistent with a stepwise mechanism. It is, however, in accord with a concerted equal rupture<sup>34a</sup> of a and b.<sup>34b</sup> Since both bonds break simultaneously with equal progress in this unsymmetrical adduct we would at least suspect that the symmetrical adducts derived from furan or 2,5-dimethylfuran and maleic anhydride also decompose in concerted rupture. The nature of the transition state for the formation of adduct must be the same as that for the decomposition of adduct by the principle of microscopic reversibility, and therefore, its mechanism must involve a simultaneous formation of two bonds.

We may now ask why the  $\alpha$ -deuterium isotope effects are smaller ( $k_H/k_D = 1.08$ ) in this system than they appear to be in other systems ( $k_H/k_D \cong 1.12$ ).<sup>14</sup> The entropy of activation for the formation of many Diels–Alder adducts in the gas phase is generally a large negative value while it is near zero for the decomposition.<sup>4a</sup> Furthermore the energies of activation for decomposition are large; they are small for the formation of adduct. Although  $\Delta S^*$  has not been measured for this reaction, it has been observed for the decomposition of the closely related *exo* adduct from 2-methylfuran and maleimide to be about 5 e.u.<sup>35</sup> From the earlier



(26) E. S. Lewis, *Tetrahedron*, **5**, 143 (1959).

(27) V. J. Shiner, Jr., *ibid.*, **5**, 243 (1959).

(28) V. J. Shiner, Jr., B. L. Murr, and G. Heinemann, *J. Am. Chem. Soc.*, **85**, 2413 (1963); V. J. Shiner, Jr., and J. S. Humphrey, Jr., *ibid.*, **85**, 2416 (1963).

(29) (a) V. J. Shiner, Jr., *ibid.*, **74**, 5285 (1952); (b) E. S. Lewis and G. M. Coppinger, *ibid.*, **76**, 796 (1954).

(30) L. S. Bartell, *ibid.*, **83**, 3567 (1961).

(31) K. Mislow, E. Simon, and H. B. Hopps, *Tetrahedron Letters*, No. **22**, 1011 (1962); K. Mislow, R. Graeve, A. J. Gordon, and H. G. Wahl, Jr., *J. Am. Chem. Soc.*, **85**, 1199 (1963); L. Melander and R. E. Carter, *ibid.*, **86**, 295 (1964).

(32) A. Streitwieser, Jr., "Molecular Orbital Theory for Organic Chemists," John Wiley and Sons, Inc., New York, N. Y., 1961, p. 158.

(33) C. E. Boozer, B. W. Ponder, J. C. Trisler, and C. E. Wightman, III, *ibid.*, **78**, 1506 (1956). This is the only study at present known to us where a  $\beta$ -effect is easily extractable from the data.

(34) (a) The word *equal* is used here only in a semiquantitative sense. Of course with our present knowledge and techniques we could not rule out a concerted "unequal" rupture of both bonds where the carbon-carbon stretching force constant for bond a has decreased to 0.55 of its original value and that for b to only 0.50 of its initial value. (b) By assuming that diene and dienophile move apart along a line bisecting the angle made by bonds a and b and in the same plane as these bonds,  $\nu_{1L}^*/\nu_{2L}^*$  can be calculated to be 1.01 (*i.e.*,  $\text{CH}_3$  vs.  $\text{CD}_3$ ) from the fragment model (ref. 23, p. 30). This approximation holds for a flat barrier if the center of masses of these groups are also on this line of movement<sup>17</sup>; it gives too low a value for a curved barrier. That the experimental value,  $k_H/k_D = 1.03$ , is not much larger than  $\nu_{1L}^*/\nu_{2L}^*$  indicates the situation where there are probably no changes in C–H force constants of the methyl group when a and b are stretched.

(35) F. Dunne and S. Seltzer, unpublished work

measurements the conclusion has been drawn that the transition state in adduct decomposition resembles the adduct in geometric form,<sup>4a,36</sup> although considerable bond breaking has taken place. If both fragments are still close in the transition state, the H-C leaving group bending force constants might not be expected to decrease as much as they do in other reactions even though considerable bond breaking has taken place. The net effect is to produce a smaller  $\alpha$ -deuterium isotope effect.

*N.m.r. Spectra.* The n.m.r. spectrum of the natural adduct I in  $\text{CHCl}_3$  is shown in Figure 1 together with their positions using  $\text{CHCl}_3$  as internal standard. The following observations should be pointed out: (1) the quartet,  $\tau$  6.63–7.03, disappears in II and reduces to two singlets in a mixture of IV and V; (2) the split single peak at  $\tau$  4.74 disappears in III with concurrent loss of splitting in the peaks at 3.42 and 3.53; and (3) loss of the large peak at  $\tau$  8.26 in compound VI. The assignments, in  $\tau$ -units, that follow from these observations are:  $\text{CH}_3$ , 8.26;  $\text{H}_Y$ , 6.96;  $\text{H}_X$ , 6.71;  $\text{H}_Z$ , 4.74;  $\text{H}_B$ , 3.69;  $\text{H}_A$ , 3.49;  $|J_{AB}| = 5.6$  c.p.s.;  $|J_{XY}| = 7.2$  c.p.s.;  $|J_{AZ} + J_{BZ}| = 1.9$  c.p.s.; and  $J_{XZ} = J_{YZ} = 0$ .

The assignment that  $\text{H}_Y$  is at higher field than  $\text{H}_X$  comes from a calculation of the difference in shift between  $\text{H}_X$  and  $\text{H}_Y$  due to the diamagnetic anisotropy of the C-C vs. the C-H bonds in an otherwise symmetrical molecule. An equation showing the magnetic environmental effect on a proton by an axially symmetrical anisotropic bond has been derived by McConnell.<sup>37</sup> This expression

$$\sigma_{av}(G) = \frac{(3 \cos^2 \theta - 1)(\chi_L - \chi_T)}{3r^3}$$

(36) M. W. Kreevoy, "Technique of Organic Chemistry," Vol. VIII, Part II, 2nd Ed., Interscience Publishers, Inc., New York, N. Y., 1963, Chapter XXIII.

(37) (a) H. McConnell, *J. Chem. Phys.*, **27**, 226 (1957); (b) see also L. M. Jackman, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," Pergamon Press Inc., New York, N. Y., 1959, pp. 112–119.

where  $\sigma_{av}(G)$  is the shielding effect experienced by a nuclei due to group G,  $r$  is the distance in centimeters of the nuclei from the center of the anisotropic bond, and  $\theta$  is the acute angle between the axis of symmetry of the bond and the line from the center of the bond to the proton, has been used successfully in many cases.<sup>37b</sup> In particular, Bothner-By and Naar-Colin<sup>38</sup> have calculated the observed difference in chemical shift between axial and equatorial protons in cyclohexane due to diamagnetic anisotropy of neighboring carbon-carbon single bonds. Using their same value of  $-5.5 \times 10^{-30}$  cm.<sup>3</sup>/molecule for  $(\chi_L - \chi_T)$  and neglecting any anisotropy due to the C-H bond,<sup>39</sup> we calculate that  $\text{H}_Y$  is shielded by 0.12 p.p.m. and  $\text{H}_X$  is deshielded by 0.03 p.p.m. Distances, as measured on a Dreiding model, are 2.40 and 3.90 Å. for  $\text{H}_Y$  and  $\text{H}_X$ , respectively; their corresponding angles are  $80^\circ$  and  $35^\circ$ , respectively. The disagreement between calculation (0.15 p.p.m.) and observation (0.25 p.p.m.) for the difference in shift between  $\text{H}_Y$  and  $\text{H}_X$  is probably not significant in view of the approximations introduced by measuring  $r$  and  $\theta$  directly from models. The direction of the shielding for both  $\text{H}_X$  and  $\text{H}_Y$  produced by the neighboring C-C bond, however, is significant. The anisotropy of the C-C bond is probably also responsible for the shift of  $\text{H}_B$  to higher field relative to  $\text{H}_A$ . These predictions are partially confirmed by examining the symmetrical *exo* adducts from furan and 2,5-dimethylfuran and maleic anhydride. In acetone as solvent, the olefinic hydrogens in the 2,5-dimethylfuran adduct are 0.25 p.p.m. higher than those in the furan adduct while the XY protons in the 2,5-dimethylfuran adduct are, unexpectedly, only 0.03 p.p.m. higher than the corresponding protons in the furan adduct.<sup>40</sup>

*Acknowledgment.* The author is indebted to Dr. D. R. Christman, Mrs. C. Paul, and Mr. T. Middleton for deuterium analyses.

(38) A. A. Bothner-By and C. Naar-Colin, *Ann. N. Y. Acad. Sci.*, **70**, 833 (1958).

(39) Reference 37b, p. 17.

(40) S. Seltzer, unpublished work.