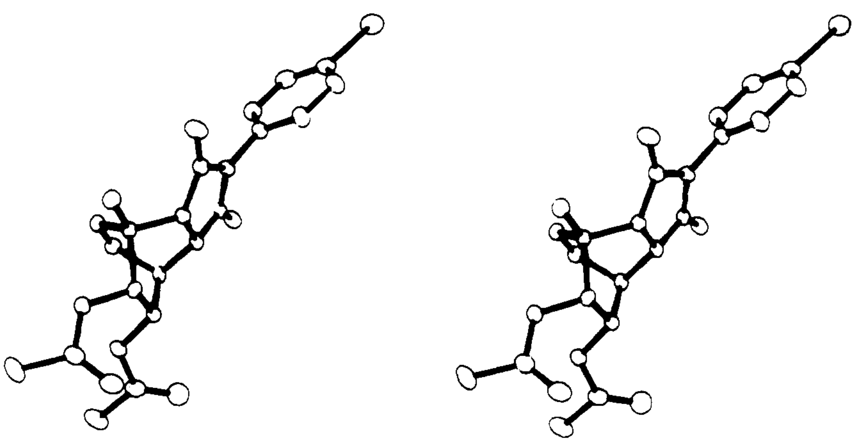

Figure 1. Stereoscopic view of **3**.

imaginary component, $\Delta f''$, of the bromine atom, and making no anomalous dispersion corrections for carbon, oxygen, or hydrogen.

The absolute configuration was determined from the X-ray diffraction data by two methods. In the first of these, each enantiomer was refined, by least-squares methods, to convergence, after inclusion of the $\Delta f''$ correction to the scattering factor of Br. These refinements resulted in *R* values of 0.057 for the 8*S*,9*R* structure and 0.061 for the 8*R*,9*S* structure. Using Hamilton's tables of significance points for *R*-value ratios,[10] the 8*R*,9*S* structure may be rejected above the 99.5% confidence level; thus, we conclude that the 8*S*,9*R* structure (Figure 1) is the correct one.

In the second method, intensity ratios were calculated for Bijvoet pairs, assuming the 8*S*,9*R* structure and including the bromine $\Delta f''$ term. For several Bijvoet pairs for which ratios quite different from 1.0 were calculated, and for which the intensity was sufficiently large to ensure small random counting error, intensity ratios were determined experimentally, using the same crystal for which the original intensity data had been collected. The results of these measurements are shown in Table I. The uniform agreement of calculated and observed ratios in the direction of deviation from 1.0 again confirms the correctness of the assumed structure, 8*S*,9*R*.

Table I. Calculated and Observed Intensity Ratios for Some Bijvoet Pairs

			$I(hkl)/I(\bar{h}\bar{k}\bar{l})$	
h	*k*	*l*	Calcd[a]	Obsd[b]
0	12	0	1.22	1.35
1	12	0	1.32	1.40
2	8	0	0.74	0.86
3	12	0	1.25	1.27
4	6	0	1.22	1.22
1	14	1	0.72	0.88
2	11	1	0.79	0.91
0	7	1	0.66	0.81
2	7	2	0.80	0.93
1	2	1	0.49	0.59
0	4	4	1.26	1.25
1	3	−2	1.29	1.27

[a] Calculated with coordinates for the 8*S*,9*R* structure and $\Delta f''$ for Br = 1.46. [b] Based only on counting statistics, the estimated error in observed ratios does not exceed 2%.

The final structure, including the determined absolute stereochemistry, is shown in Figure 1. There are no unusual bond distances, bond angles, or conformational features. A description of the structure determination and refinement, as well as details of molecular geometry, will be published later (R. E. D. and A. G.). The absolute stereochemistry of the toluenediol has also been determined by chemical and spectrophotometric studies.[11]

Acknowledgments. D. T. G. and V. M. K. gratefully acknowledge the support of Grants ES-000537 from the National Institutes of Health and F-440 from the Robert A. Welch Foundation. D. T. G. is a recipient of Career Development Award 1 K04 ES-70088 from the National Institutes of Health. R. E. D. and A. G. gratefully acknowledge support of the X-ray studies by Robert A. Welch Foundation Grant F-233.

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(10) W. C. Hamilton, *Acta Crystallogr.*, **18**, 502 (1965).

(11) H. Ziffer, D. M. Jerina, D. T. Gibson, and V. M. Kobal, *J. Amer. Chem. Soc.*, submitted for publication.

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Secondary Deuterium Isotope Effects in Pericyclic Reactions. The Thermal Rearrangement of Dideuteriobiscyclopropylidene

Sir:

For some time now we have been intrigued by the observation in our laboratory[1] and others[2] of a normal isotope effect in the product-forming destruction of resonance-stabilized biradicals. Such an effect in an apparently bond-forming process was of obvious mechanistic significance, since simple bond formation is generally expected to give rise to an *inverse* secondary deuterium isotope effect.

In a recent paper, we proposed that such isotope effects derive from *rotation* of a methylene group of a

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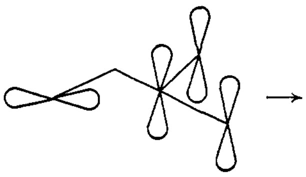
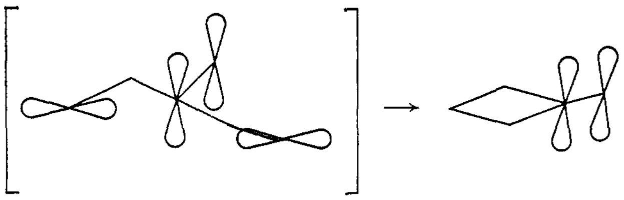
(1) (a) W. R. Dolbier, Jr., and S.-H. Dai, *J. Amer. Chem. Soc.*, **94**, 3946 (1972); (b) W. R. Dolbier, Jr., and J. H. Alonso, *ibid.*, **94**, 2544 (1972).

(2) (a) R. J. Crawford and D. M. Cameron, *ibid.*, **88**, 2589 (1966); (b) W. R. Moore, P. D. Mogolesko, and D. D. Traficante, *ibid.*, **94**, 4753 (1972).

conjugated system (**1**) to a nonconjugated, orthogonal conformation in the transition state (**2**), as shown for the cyclization of a typical biradical **1**. In such cases, the activation energy[3] for the cyclization process would derive from the process of rotation out of conjugation.

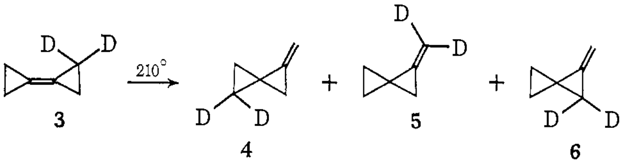


1



2

In an effort to promote further understanding of the mechanism of the cyclization of stabilized biradicals and to emphasize the effectiveness of secondary deuterium isotope effects as a tool in probing the nature of transition states in pericyclic reactions, we would like to report our investigation of the thermal rearrangement of dideuteriobiscyclopropylidene (**3**)[4] to the deuterated methylenespiropentanes **4**, **5**, and **6**. Secondary deuterium isotope effects on a methylenecyclopropane rearrangement have not yet been reported. It will be shown that knowledge of these effects does indeed allow significant insight into the mechanism of such processes. In the interpretation of these isotope effects we will want to emphasize the ability to rationalize the effects mechanistically without resorting to complex theoretical calculations.



In the rearrangement of **3** two distinct isotope effects are operative as depicted in Scheme I.[8] The values of these isotope effects are reflected by the relative amounts of products **4**, **5**, and **6**, and these values may be obtained directly from the nmr spectrum of the mixture of **4**, **5**, and **6** (see Table I).

Scheme I

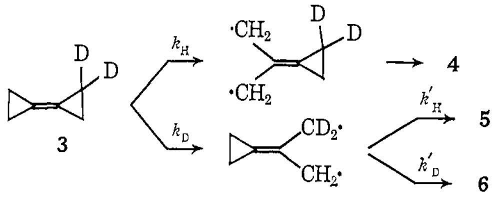


Table I. Intramolecular Isotope Effects for the Thermal Reorganization of **3** at 214 ± 2°

Run	Nmr ratios[a,b]	
	5:**6**	**4**:**5** + **6**
1	1.15	1.21
2	1.12	1.23
3	1.14	1.28
Av	1.14 ± 0.02	1.24 ± 0.03

[a] The nmr ratios were obtained from multiple nmr integrations on samples of glpc-purified mixtures of **4**, **5**, and **6** obtained from three independent reactions. The maximum observed error in these ratios, expressed as standard deviation, was 2%.

Where x, y, and z equal the integrated areas of cyclopropyl, allylic, and vinylic proton absorptions, respectively

$$5/6 = \frac{x + y - 2z}{x + z - 2y} = \left(\frac{k_H'}{k_D'}\right)_{cyclzn} = 1.14 \pm 0.02$$

$$\frac{4}{5 + 6} = \frac{2y + 2z - x}{2x - y - z} = \left(\frac{k_H}{k_D}\right)_{cleav} = 1.24 \pm 0.03$$

The observed isotope effects are consistent with biradical mechanisms a and b depicted in Scheme II, and also with one possible concerted mechanism to be discussed below. It is believed that the large normal $(k_H/k_D)_{cleav}$ arises from formation of transition state A, where C–C bond breaking is occurring, with some CH_2 twisting, to produce either the planar trimethylenemethane intermediates **7** and **8** or the "pivot" intermediate **9**,[9] either of which can cyclize as shown to methylenespiropentane. The cleavage isotope effect can thus be rationalized in terms of a "steric" secondary deuterium isotope effect.[10] That is, a normal isotope effect is expected if the transition state is "looser" or "less rigid" than the starting material. One very significant vibrational change undergone in proceeding to the transition state is the drastic lowering of the torsional force constant for the CH_2 twisting motion.[11] This is a reflection of the reduction of the rotational barrier for the CH_2 twisting motion as the C–C bond is weakened.

The $(k_H/k_D)_{cyclzn}$ is similar in magnitude to those observed in other cyclization processes.[1,2,12] This normal effect can be rationalized *via* process a as arising from a reduction in "crowding" and/or rigidity of the species **8** in its procession to transition state B. The ef-

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[3] Estimated for cyclization of trimethylenemethane as ~13 kcal/mol: J. J. Gajewski, *ibid.*, 93, 4450 (1971).

[4] **3** was prepared by a process essentially identical with that used by Conia[5] to synthesize biscyclopropylidine, except that dideuteriomethylenecyclopropane[6,7] was utilized as the starting material.

(5) P. LePerchec and J. M. Conia, *Tetrahedron Lett.*, 1587 (1970); we thank Professor Conia for kindly making his experimental details available to us.

(6) W. R. Dolbier, Jr., and J. H. Alonso, *J. Chem. Soc., Chem. Commun.*, in press.

(7) Nmr analysis of the dideuteriomethylenecyclopropane, and of each subsequent precursor of **3**, indicated *no* significant vinyl proton absorption, thus indicating **3** to be essentially isotopically pure.

(8) The cleavage step was shown to be irreversible and thus rate determining when the product mixture of **4**, **5** and **6** was resubjected to heating at a higher temperature (244°) and products **5** and **6** equilibrated but not product **4**.

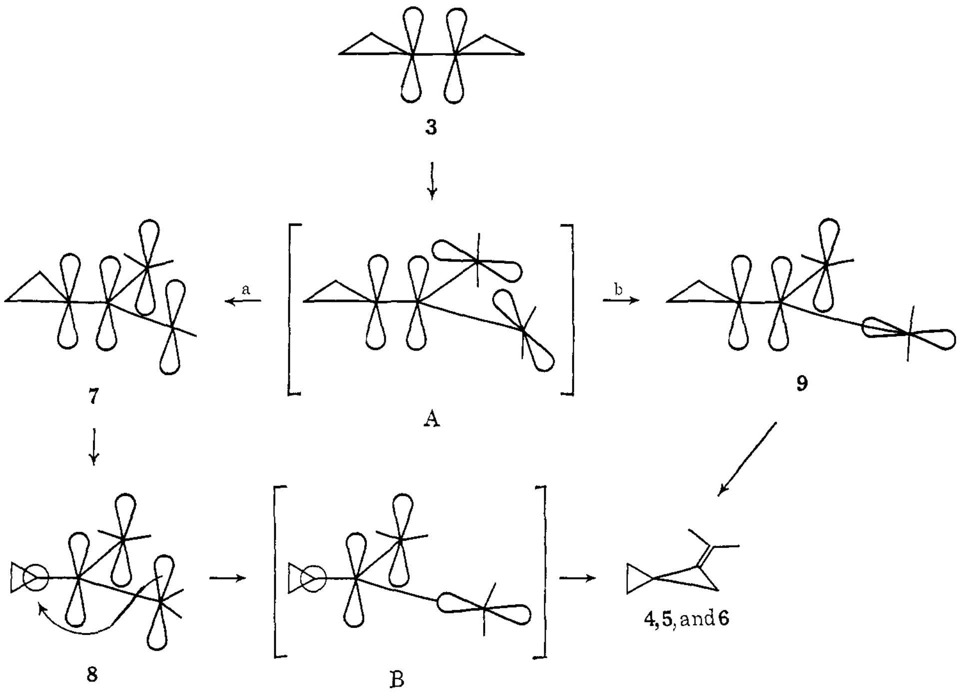
(9) W. von E. Doering and L. Buladeanu, *Tetrahedron*, 29, 499 (1973).

(10) C. J. Collins and N. S. Bowman, "Isotope Effects in Chemical Reactions," Van Nostrand Reinhold Co., New York, N. Y., 1970.

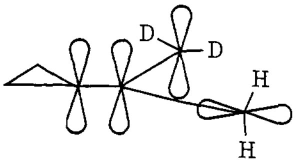
(11) I. Safarik and O. P. Strausz, *J. Phys. Chem.*, 76, 3613 (1972).

(12) The large value of $k_H/k_D = 1.37$ observed by Crawford for the cyclization of trimethylenemethane[2a] may indeed provide evidence for the planar nature of the species in his reaction, since *two* methylenes would in this case have to rotate toward orthogonality and thus the isotope effect should be the *square* of ours, as indeed it approximately is.

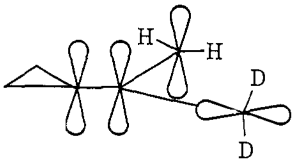
Scheme II



fect can be rationalized for path b if one considers that intermediate **9a** will be lower in energy than **9b**.[13]

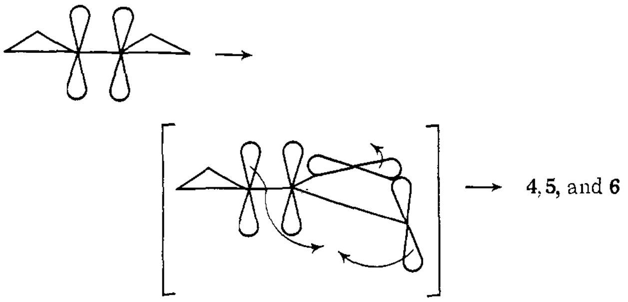


9a



9b

In considering a concerted mechanism, the "pivot" type of transition state (transition state C) can rationalize the data if one assumes that the pivot methylene is the loosest CH_2 group in the transition state.



C

While a complete distinguishing of the mechanism is not possible in this case, significant insight is gained into the mechanistic process, insight which will undoubtedly be magnified as more analogy becomes available relating to secondary deuterium isotope effects in sigmatropic processes. In these and in our earlier results we want to emphasize that the isotope effect data may be interpreted using a simple, rule of thumb, "steric" interpretation of secondary isotope effects and that useful mechanistic conclusions can be deduced without rigorous theoretical analysis.

Acknowledgment. The authors thank the National Science Foundation for partial support of this research.

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Received March 3, 1973

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[13] This is likely because of the greater steric requirement of CH_2 *vs.* CD_2 and, as described earlier, because of the differences between a planar and an orthogonal allylic CH_2 group in the twisting vibration.

Ring Inversion in Cyclohexanone

Sir:

We wish to report the first experimental determination of the free-energy barrier ($\Delta G^{\ddagger}$) for ring inversion in cyclohexanone.[1] For reasons discussed below, we

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[1] The claim by Jensen and Beck[2] that the "most probable" $\Delta G^{\ddagger}$ for ring inversion in cyclohexanone is 4.9 ± 0.3 kcal/mol was based on the observation that the proton nmr lines of this ketone (or its *2,2,6,6-d*$_4$ derivative) are broader than the tetramethylsilane line at −168 to −172°. This extra broadening was attributed to the rate constant for ring inversion being in an intermediate region between the slow and fast exchange limits. However, there are large and *different* contributions to the line widths at low temperatures as a result of dipole–dipole relaxation, and thus no valid deduction about $\Delta G^{\ddagger}$ can be made from these experiments. Furthermore, the "confident" conclusion[2] that $\Delta G^{\ddagger}$ has a maximum value of 5.1 kcal/mol (5.2 kcal/mol for the tetradeuterio derivative) depends on the absence of near-coincidences in chemical shifts between the axial and equatorial protons on a CH_2 group. Such near-coincidences are found in 1,4-dioxane[3] and cannot be eliminated with real confidence for cyclohexanone. The barrier to ring inversion in 4,4-difluorocyclohexanone has been stated to be ≤ 2.3 kcal/mol because of the absence of broadening of the fluorine resonance at −183°.[4] Although near-coincidences in chemical shifts are less likely for fluorines than for protons,[5] such a possibility cannot be completely ruled out. The only well-established barriers for ring inversion in six-membered ketones are for 2,2,5,5-tetramethylcyclohexanone ($\Delta G^{\ddagger}$ = 8.1 kcal/mol)[6] and 2,2,5,5-tetramethyl-3-methylenecyclohexanone ($\Delta G^{\ddagger}$ = 5.9 kcal/mol),[7] where substituent effects are undoubtedly quite large.

[2] F. R. Jensen and B. H. Beck, *J. Amer. Chem. Soc.*, **90**, 1066 (1968).

[3] F. A. L. Anet and J. Sandström, *Chem. Commun.*, 1558 (1971); F. R. Jensen and R. A. Neese, *J. Amer. Chem. Soc.*, **93**, 6329 (1971).

[4] R. E. Lack, C. Ganter, and J. D. Roberts, *ibid.*, **90**, 7001 (1968).

[5] S. L. Spassov, D. L. Griffith, E. S. Glazer, J. Nagarajan, and J. D. Roberts, *ibid.*, **89**, 88 (1967).

[6] M. Bernard and M. St. Jacques, *Chem. Commun.*, 1097 (1970).

[7] M. Bernard, F. Sauriol, and M. St. Jacques, *J. Amer. Chem. Soc.*, **94**, 8624 (1972).