(12) B. Ancian, J.-P. Doucet, and J-E. Dubois, *J. Am. Chem. Soc.*, **98**, 4764 (1976).
(13) Our data do not distinguish between these alternatives if the cyclopropyl group in **2a** and **2b** is considered to be donating electrons to the cationic center.
(14) A preliminary report of some of our results on this cation has already appeared: D. G. Farnum and R. E. Botto, *Tetrahedron Lett.*, 4013 (1975).
(15) E. Lippmaa, T. Pehk, J. Paasivirta, N. Belikova, and A. Plate, *Org. Magn. Reson.*, **2**, 581 (1970).
(16) The calculated ratio **3**:**3a** is relatively independent of the chemical shift assigned. For example, a choice of 40 ppm gives a ratio of 74:26. Neither is the ρ value for the Hammett correlation affected.
(17) H. C. Brown and Y. Okamoto, *J. Org. Chem.*, **22**, 485 (1957).
(18) The values of C(5) and C(6) were chosen to give the correct slope and the correct value for the bis(trifluoromethyl) substituted derivative.
(19) Note, however, the small ρ value if an equilibrium is assumed.
(20) J. B. Stothers, J. R. Swenson, and C. T. Tan, *Can. J. Chem.*, **53**, 581 (1975).
(21) The argument, given in detail in our earlier paper,[1] is not reproduced here, since other arguments to be given are simpler.
(22) This concentration is relatively independent of the chemical shift chosen for the bridgehead carbon. We have chosen 100 ppm as an upper limit, which is least favorable to our case.
(23) Estimates of the ^{13}C chemical shift per unit positive charge vary from 150 to 300 ppm.[8] We have chosen 300 ppm as an upper limit, which is least favorable to our case.
(24) We have also reported these rearrangements,[1] though we did not study them quantitatively.
(25) T. Sorenson, personal communication.
(26) G. A. Olah, A. M. White, J. R. DeMember, A. Commeyras, and C. Y. Lui, *J. Am. Chem. Soc.*, **92**, 4627 (1970).
(27) S. Cristol, W. Siefert, and B. Soloway, *J. Am. Chem. Soc.*, **82**, 2351 (1960).
(28) K. B. Wiberg and B. A. Hess, Jr., *J. Org. Chem.*, **31**, 2250 (1966).
(29) P. K. Freeman, D. M. Balls, and D. J. Brown, *J. Org. Chem.*, **33**, 2211 (1968).

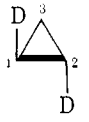
A Test for "Wrong-Bond" Rupture in the Thermal Structural Isomerization of Phenylcyclopropane and a Confirmation of the Two-Center Epimerization Mechanism in Its Stereomutation[1]

John T. Wood, Jonathan S. Arney, David Cortès, and Jerome A. Berson*

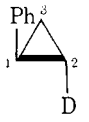
Contribution from the Department of Chemistry, Yale University, New Haven, Connecticut 06520. *Received November 21, 1977*

Abstract: The major products of the thermal structural isomerization of phenylcyclopropane at 340–360 °C are *trans*- and *cis*-β-methylstyrene and allylbenzene. A small amount of *n*-propylbenzene also is found, but the product distribution is quite different from that in the literature, where *n*-propylbenzene and α-methylstyrene were reported to be the major products. Synthesis of the three isomers of 1-phenylcyclopropane-*2,3-d*$_2$ can be achieved by routes terminating in a stereospecific Haller–Bauer cleavage. The trans isomer, $[\alpha]_D$ +0.519° (neat, 0.5 dm), loses optical activity at 309.5 °C in a first-order reaction. By combining the rate constant for this reaction with that for the trans–cis isomerization of *trans*-1-phenylcyclopropane-*2-d*, it is possible to conclude that the stereomutation at C_1, the phenyl-bearing carbon, occurs in synchrony with stereomutations at C_2 and C_3.

Thermal stereomutations of cyclopropane-*1,2-d*$_2$ (**1**) and 1-phenylcyclopropane-*2-d* (**2**) employ a two-center epimerization mechanism, in agreement with the theoretically predicted synchronous pairwise rotation of ring members.[2-4] In **1**, the molecular symmetry requires that each of the C–C bonds



1-*1,2-d*$_2$

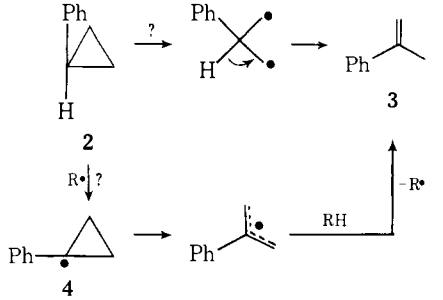


2-*2-d*

must participate in the stereomutation at the same rate, except for a small secondary isotope effect.[2] In **2**, however, the 1,2 and 1,3 bonds are equivalent, but the 2,3 bond is unique. This has prevented a complete kinetic analysis, and it has been possible to say only that the rotation of C_1 is strongly coupled to that of C_2 (and by symmetry C_3) (>96% double rotation).[3] The rotation of C_2 in synchrony with that of C_1 constitutes about 80% of the total C_2 stereomutation, the remainder being made up of C_2–C_3 double rotation and C_2 single rotation in a ratio that cannot be determined at the monodeuterio level of substitution.[3]

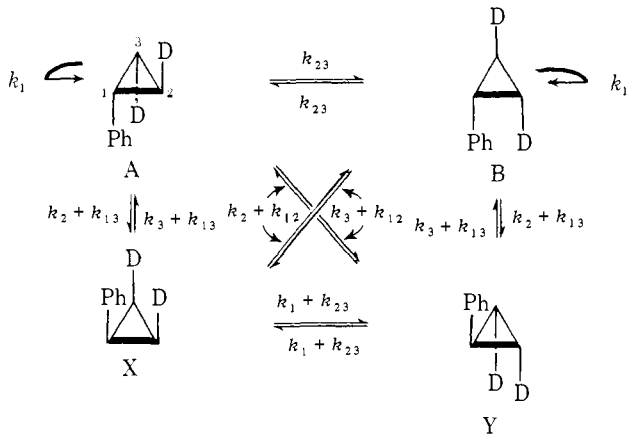
The mechanistic assignment of this last 20% of C_2 stereomutation has significance for the general problem of reaction at sites other than the most substituted one in cyclopropane stereomutations. Should the mechanism prove to have a substantial component of reaction at the "wrong" bond (C_2–C_3 double rotation), the interpretation of many previous studies would be in jeopardy, since analysis of the kinetic data in the majority of the cases[4] has depended on the assumption that reaction occurs only at the most substituted bond.

Although intuitive arguments, bond energy considerations,[5,6] and quantum mechanical calculations of the reaction pathways[7] all suggest that C_1–C_2 cleavage should predominate strongly over C_2–C_3 in the stereomutation of phenylcyclopropane, it nevertheless would be comforting to have some experimental assurance. We were particularly drawn to investigate the phenylcyclopropane system by the intriguing report of Leermakers and Ross[8] that pyrolysis of this hydrocarbon gave α-methylsytrene (**3**) as a major product of the *structural* isomerization. Although this finding is not necessarily relevant to the stereomutation, and although a radical chain mechanism[8] via **4** could rationalize the result, the ex-



0002-7863/78/1500-3855$01.00/0

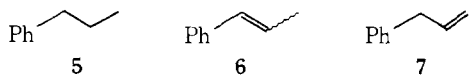
Scheme I. Stereomutation of 1-Phenylcyclopropane-2,3-d_2



perimental evidence for such a mechanism was not decisive, and the possibility remained open that **3** was a product of "wrong-bond" cleavage in **2.**

The purposes of the present study were to search for "wrong-bond" cleavage in both the structural and stereochemical isomerizations of **2.** The first objective now has been achieved by the demonstration that α-methylstyrene is not a significant product of the pyrolysis of **2.** The second has eluded us so far, but in its pursuit, we have been able to confirm independently the synchronous double rotation of the phenyl-bearing carbon (C_1) and one of the methylene groups of **2.**

Structural Isomerization of Phenylcyclopropane. Leermakers and Ross[8] studied the gas-phase pyrolysis of phenylcyclopropane at 350 °C. They found, in addition to substantial amounts of fragmentation products (methane, ethane, ethylene, etc.), only *n*-propylbenzene (**5,** 39.7%), α-methylstyrene (**3,** 38.2%), and β-methylstyrene (**6,** stereochemistry unspecified, 3.3%) as C_9 products. This is strikingly different from the distribution that might have been expected by analogy to a number of other substituted cyclopropanes,[4,6,9-13] which



5 6 7

show predominant rupture of the substituted bond. On this basis, the major products should have been the β-methylstyrenes (**6**) and allylbenzene (**7**). The origin of the large amount of propylbenzene reported, apparently a disproportionation product, also was difficult to understand.

In our hands, the products of this pyrolysis differed significantly from those found by Leermakers and Ross.[8] In addition to small amounts of several products, including toluene, styrene, ethylbenzene, and indene, identified only by gas chromatographic (GC) retention time, we have established by GC isolation as well as both infrared and nuclear magnetic resonance spectroscopy that *trans*-β-methylstyrene (**6,** 46%), *cis*-β-methylstyrene (**6,** 13%), and allylbenzene (**7,** 25%) are the major products. There is some propylbenzene (**5,** 8%), suggesting that **6** and/or **7** may have served as hydrogen acceptors in the formation of indene[14] or other disproportionation products. By a careful search for α-methylstyrene **3,** we have established that, if present, it constitutes less than 0.1% of the pyrolysis products.

In speculating about the causes of the disparities between the results, we note that the previous[8] GC analyses used a di-*n*-decyl phthalate column. For preliminary analyses, we used a di-*n*-nonyl phthalate column, which might be expected to have similar properties. On this column authentic allylbenzene and propylbenzene had nearly identical retention times, although the two hydrocarbons were analytically separable on a Poropak-Q column. *cis*-β-Methylstyrene and α-methylstyrene were separable on the nonyl phthalate column, although their retention times were similar.

The ratio of the sum of the products from C_1–C_2 cleavage (**5–7**) to that from C_2–C_3 cleavage (**3**) is at least 820:1. This corresponds to a minimum activation energy preference ($\Delta\Delta G^{\ddagger}$) for cleavage of the substituted bond of 8.6 kcal/mol in the structural isomerization.

Stereomutation of Optically Active *trans*-Phenylcyclopropane-2,3-d_2. The rationale of these experiments may be followed by reference to Scheme I. As before,[2,3] two-center and one-center epimerization rate constants are given double and single indexes, respectively, that is, k_{12}, k_{13}, k_{23}, and k_1, k_2 ($= k_3$).

Note that the peculiar symmetry properties in this system make the single epimerization at C_1 undetectable in the trans compound A and its enantiomer B. However, the rate constant for this process is not necessarily zero a priori. In principle, it could be evaluated by a study of the kinetics of the interconversion of the syn-cis and anti-cis isomers X and Y. Also, by symmetry, $k_2 = k_3$, and $k_{12} = k_{13}$, to a very good approximation. We refer to these single and double rotation rate constants as k_s and k_d, respectively. The presence of a second deuterium label in these molecules means that the rate constants of Scheme I will differ slightly from those representing the corresponding reactions in phenylcyclopropane-2-*d*,[2,3] because of a small secondary isotope effect, but this difference will not cause any difficulty.

Three experiments will suffice, in principle, to complete the kinetic analysis of Scheme I. Experiment 1 follows the rate of trans–cis isomerization, where the concentration of the trans component $T = A + B$, and that of the cis component $C = X + Y$. The unbracketed italic capital letters represent molar concentrations. This is a first-order reaction with rate constant k_i given by

$$k_i = (1/t) \ln [(T_0 - C_0)/(T - C)] = 4(k_d + k_s) \quad (1)$$

Experiment 2 monitors the loss of optical activity in a sample containing optically active trans. Suppose that initially the concentration of enantiomer A is in excess, i.e., $A_0 > B_0$. Because the cis and trans components of the mixture differ only in the stereochemical disposition of the isotopic labels, they are not readily separable. Consequently, it will be necessary to follow the total rotation of the mixture. The rate at which optical activity is lost will be the sum of the rate of formation of the (achiral) cis component (X + Y) and twice the rate of formation of the antipodal trans component B. This can be expressed in the form

$$\mathrm{d}(C + 2B)/\mathrm{d}t = \mathrm{d}(A - B)/\mathrm{d}t = 2(k_{23} + k_d + k_s)(A - B) \quad (2)$$

The optical rotation is directly proportional to $(A - B)$, and integration of eq 2 then gives

$$k_\alpha = (1/t) \ln (\alpha_0/\alpha) = 2(k_{23} + k_d + k_s) \quad (3)$$

Note that in this system optical deactivation is in principle a first-order process, whereas previously[2,3] it was not. By combination of eq 1 and 3, we obtain

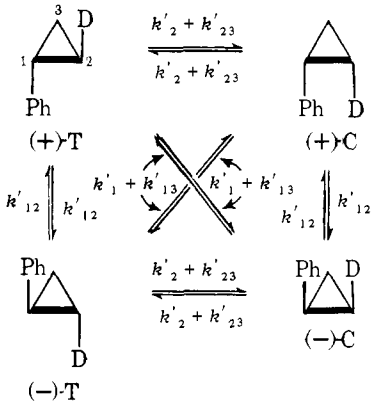
$$k_{23} = (2k_\alpha - k_i)/4 \quad (4)$$

This strategy aims directly at an evaluation of the "wrong-bond" component of the stereomutation.

Experiment 3 is designed to establish independently the value of the rate constant, k_1, for single rotation of the phenyl-bearing carbon. There are two approaches to this goal.

Experiment 3a follows the pyrolysis of a sample enriched in one of the cis isomers, for example, X. Thus, $X_0 > Y_0$, and

Scheme II



the rate of isomerization may be expressed in first-order form with the rate constant k_c, as in

$$-\mathrm{d}(X-Y)/\mathrm{d}t = 2(k_d + k_s + k_1 + k_{23})(X-Y) \quad (5)$$

$$k_c = (1/t)\ln[(X_0 - Y_0)/(X-Y)] = 2(k_d + k_s + k_1 + k_{23}) \quad (6)$$

From eq 1 and 6, we obtain

$$k_1 = \frac{2k_c - k_i}{4} - k_{23} \quad (7)$$

or alternatively, we can equate k_{23} in eq 4 to k_{23} in eq 7 to give

$$k_1 = (k_c - k_\alpha)/2 \quad (8)$$

Experiment 3b combines k_α, the rate constant for optical deactivation obtained in experiment 2, with the first-order rate constant, k_i', obtained in the previous study[2,3] of the stereomutation at 309.5 °C in the monodeuterio system. Note that, although both k_i (experiment 1) in the dideuterio case and k_i' in the monodeuterio case measure the kinetics of trans-cis isomerization, they are made up of different mechanistic rate constants, as can be seen by a comparison of eq 1, derived from Scheme I, with

$$k_i' = 2(k_1' + k_2' + k_{23}' + k_{13}') \quad (9)$$

derived from Scheme II.[2,3]

From eq 9 and 3, we may write

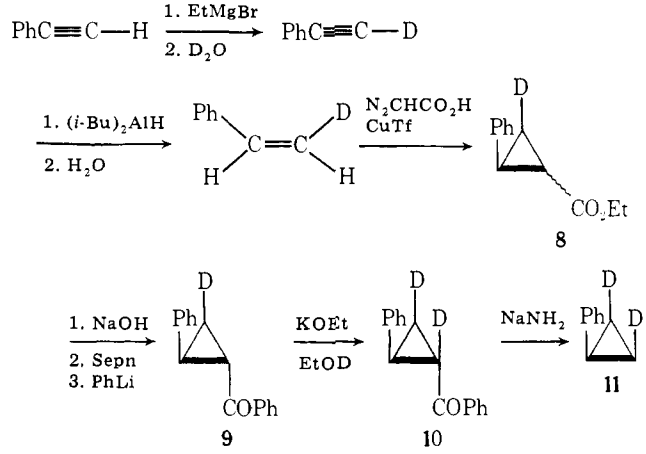
$$k_i' - k_\alpha = 2k_1' + 2(k_{13}' - k_{12}) + 2[(k_{23}' + k_2') - (k_{23} + k_2)] \quad (10)$$

To a good approximation, $k_{13}' - k_{12} \simeq k_{13}' - k_{12}'$, since both sides of the equation compare a double rotation of an undeuterated and a deuterated methylene group. From the previous work,[2,3] we may safely write for the reaction at 309.5 °C $k_{13}' - k_{12} \simeq 0.1 \times 10^{-5}\ \mathrm{s}^{-1}$. Also, we know[2,3] that $k_{23}' + k_2' = 0.19 \times 10^{-5}\ \mathrm{s}^{-1}$. If we assume the usual 10% isotope effect per deuterium, $(k_{23}' + k_2')/(k_{23} + k_2) = 1.10$, then $(k_{23}' + k_2') - (k_{23} + k_2) = 0.02 \times 10^{-5}\ \mathrm{s}^{-1}$. Substituting these values into eq 10, we obtain

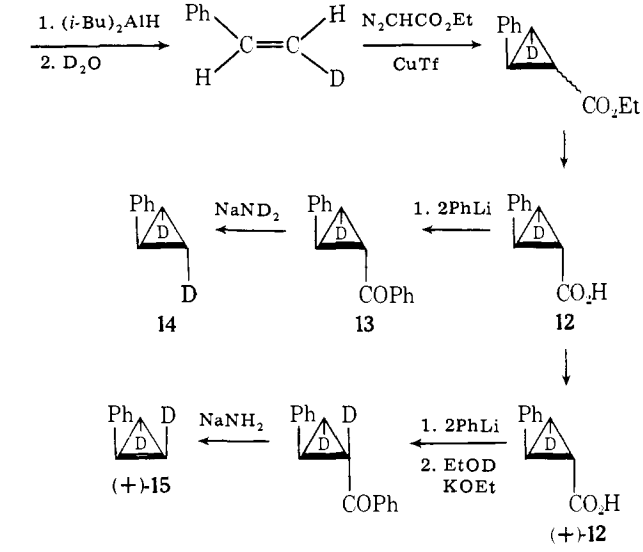
$$k_1' = \frac{k_i' - k_\alpha}{2} - 0.12 \times 10^{-5}\ \mathrm{s}^{-1} \quad (11)$$

Synthesis of the Phenylcyclopropane-2,3-d_2 Stereoisomers. Styrene-*cis*-β-*d*, prepared by treatment of phenylacetylene-β-*d* successively with diisobutylaluminum hydride[15] and H_2O, reacted with ethyl diazoacetate under cuprous trifluoromethanesulfonate catalysis[16] to give a mixture of ethyl phenylcyclopropanecarboxylates, **8**, in which the relative stereochemistry of Ph and D was fixed as cis (Scheme III). Saponification of the esters and recrystallization of the mixed acids

Scheme III



Scheme IV



gave pure *trans*-2 phenylcyclopropanecarboxylic acid-*cis*-3-*d*, which, upon reaction with phenyllithium, gave the corresponding benzoyl phenylcyclopropane, **9**. A second deuterium was introduced by exchange with EtOD/KOEt, and the dideuterio ketone **10** was subjected to a stereospecific[2,3,17] Haller-Bauer cleavage[18] with a benzene suspension of $NaNH_2$ according to the procedure described previously,[2,3] to give phenylcyclopropane-*cis*,*cis*-2,3-d_2 (**11**).

Styrene-*trans*-β-*d*, prepared by treatment of phenylacetylene successively with $(i\text{-Bu})_2AlH$ and D_2O, served as a common synthetic intermediate for the preparation of the syn-cis (**14**) and optically active trans (**15**) isomers (Scheme IV). One sample of the monodeuterio acid, **12**, obtained by the same cyclopropanation sequence as before, was converted to the benzoyl compound, **13**, and a second deuterium was introduced by Haller-Bauer cleavage[17] with $NaND_2$, to give the anti-cis compound **14**. Another sample of the monodeuterio acid **12** was resolved via the quinine and brucine salts to give 92% enantiomerically pure (+) acid. The absolute configuration and enantiomeric purity were assigned by analogy to those for the unlabeled acid,[19] on the assumption that the deuterium makes a negligible contribution. The second deuterium was introduced by exchange of the α-carbonyl proton in the optically active benzoyl derivative. Haller-Bauer cleavage $NaNH_2$ then led to the optically active trans hydrocarbon **15**, α^5_D +0.519° (0.5 dm, neat).

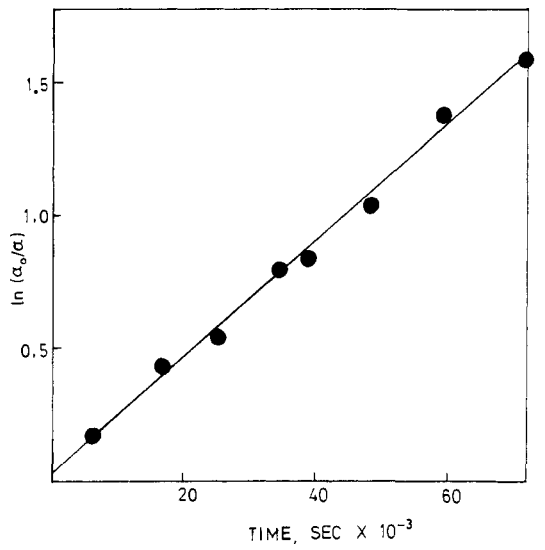


Figure 1. Optical deactivation of **2**-*2-d* in the gas phase at 309.5 °C. The line shows the least-squares fit of the data.

Kinetics of the Optical Deactivation of (+)-Phenylcyclopropane-*2,3-d*$_2$. In the previous synthesis[2,3] of monodeuteriophenylcyclopropane, less than 1% of dideuterio compound was present in the final samples. The mass spectrometric determination that the present nominally dideuterated samples of **11**, **14**, and **15** contained 5-10% of trideuterio material therefore came as an unpleasant surprise. Direct deuterium magnetic resonance spectroscopy showed not only the absorptions at high field due to the C_2 and C_3 deuteriums but also small resonances at the chemical shift of the benzylic position (C_1) and, in the case of the trans compound **15**, of the aromatic ring positions. The origin of these small extra labelings is obscure. The synthetic intermediates were routinely monitored by ^{1}H NMR, but evidently this was too insensitive to disclose the contaminants. We were able to establish that the exchange of the α-carbonyl proton of *trans*-1-phenyl-2-benzoylcyclopropane-*3-d* (**13**) with EtOD/KOEt in hot dimethoxyethane gave recovered ketone containing about 5% d_3 components, as determined by mass spectroscopy. This may account for some of the unwanted deuterium in the trans (**15**) and anti-cis (**10**) hydrocarbons, but since the intermediate in the preparation of the syn-cis isomer (**14**) (Scheme IV) had not been subjected to this exchange, there must be an additional source. In any case, these extra labelings are damaging to some of the proposed kinetic studies, which depend upon infrared spectrophotometry for accurate analysis of the three stereoisomers. The presence of trideuterio components in the starting materials and their conversion during pyrolysis to trideuterio isomers with different and undefined infrared spectra could well constitute an uncontrollable interference and made us suspicious of any kinetic conclusions to be drawn from infrared analyses (experiments 1 and 3a).

However, the following argument shows that the presence of other than d_2 in the optically active sample of (+)-**15** would not interfere with an accurate determination of the optical deactivation rate constant, k_α, and hence that experiment 3b can be carried out. The sample contained 1.4% d_0, 19.3% d_1, 74.0% d_2, and 5.4% d_3 components. The d_0 compound is achiral and could not contribute to the rotation except as a diluent. Both d_1 and d_3 are chiral, and their combined rotation may be represented as $\alpha_{1,3}$, whereas that of the d_2 is α_2. The total deactivation rate may be expressed as

$$-d\alpha/dt = k_\alpha\alpha_2 + k_x\alpha_{1,3} \quad (12)$$

where k_α is the rate constant of interest in the context of experiment 3b, and k_x is the rate constant for the (assumed) first-order deactivation of the d_1 and d_3 components. The experimental plot of ln (α/α_0) vs. time for such a situation would be linear in only six possible cases:

(1) $k_\alpha = k_x$. In this case the observed rate constant would be simply k_α. This case might prevail if, for example, a d_3 species labeled in the phenyl ring were mainly responsible for $\alpha_{1,3}$.

(2) $k_x = 0$. Here again, k_α would be observed. However, this case can be ruled out since it predicts an asymptotic decline of the optical activity to a nonzero residual rotation rather than to the "infinite time" value of zero actually observed.

(3) $\alpha_{1,3} = 0$. Here the isotopic impurities would simply act as diluents, and k_α again would be found.

(4) $\alpha_{1,3} = \alpha_2$. The observed rate constant would be $k_\alpha + k_x$. This situation seems highly unlikely, since it would require that the rotatory contribution of the d_1 and d_3 components equal that of the d_2. From the previous work,[2,3] it is known that the (+)-*trans*-2-phenylcyclopropanecarboxylic acid is configurationally correlated with (−)-*trans*-phenylcyclopropane-*2-d*, whereas Scheme IV shows this acid to be configurationally correlated with (+)-phenylcyclopropane-*trans-2,3-d*$_2$ (**15**). Thus, the d_1 component in the present sample is (−), and its rotation cancels part of the rotation of the (+) components. Since the d_3 component constitutes only 5% of the sample, its specific rotation would have to be more than 20 times that of the d_2 in order for $\alpha_{1,3}$ and α_2 to be equal.

(5) $\alpha_2 = 0$. In this case, the observed rate constant would be k_x.

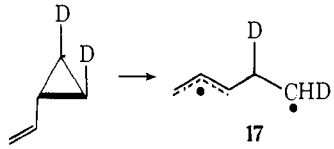
(6) $k_\alpha = 0$. This is only a formal case, which is included for completeness.

All other situations would result in a nonlinear first-order plot of the kinetic data for optical deactivation. We can estimate the extent of the curvature to be expected in the most worrisome hypothetical case, that is, when $\alpha_{1,3}$ made an appreciable contribution to the total rotation and when k_x was of the same order of magnitude as k_α. For example, if k_α and k_x were 2.6 and 1.3×10^{-5} s^{-1}, respectively, and if α_2 and $\alpha_{1,3}$ were 1.00 and 0.35°, respectively, the ln (α_0/α) vs. time plot would show an initial approximately linear portion with an apparent first-order rate constant of about 2.3×10^{-5} s^{-1}, or 13% below the "true" value of k_α. The plot, however, would show obvious convex deviation from linearity after about 1 half-life.

In the event, the pyrolysis of the sample of (+)-**15** in the gas phase at 309.5 °C showed good adherence to a first-order rate law to 80% of complete optical inactivation (>2 half-lives, Figure 1). After 20 half-lives, the optical rotation of the sample was $\alpha = 0.000 \pm 0.002°$. The observed least-squares rate constant from the eight kinetic points was $(2.21 \pm 0.03) \times 10^{-5}$ s^{-1}. In the light of the previous discussion, we may use this figure as the value of k_α in the context of experiment 3b.

From the value of k_1' observed earlier,[2,3] 2.48×10^{-5} s^{-1}, the present value of k_α, and eq 11, we calculate $k_1' = 0.015 \times 10^{-5}$ s^{-1}. Previously,[2,3] the total stereomutation of C_1 was represented by $k_1' + k_{12}' + k_{13}' = 2.02 \times 10^{-5}$ s^{-1}. The present value of k_1' would correspond to about 0.7% contribution from a single rotation mechanism at C_1. The experimental error might permit this number to be somewhat higher, but there is essential agreement with the previous conclusion[2,3] that no more than about 4% of the C_1 stereomutation can involve one-center epimerization. The two results, obtained with independent synthetic and kinetic techniques, offer assurance that the observations interpreted as synchronous double rotations are characteristic of phenylcyclopropane and not of an unknown impurity.

There remains a puzzling question. Why does vinylcyclopropane not adhere to the two-center epimerization mechanism? Instead, its stereomutation seems to involve a stereorandom intermediate, as in **16** → **17**.[20] Among other hypoth-



16 17

eses, we have considered the possibility that the phenylcyclopropane stereomutation may be a reversible 1,3-sigmatropic rearrangement, via bicyclo[4.3.0]nona-2,4,6-triene intermediates. The counterpart of this reaction, the vinylcyclopropane → cyclopentene rearrangement which accompanies the stereomutation of vinylcyclopropane,[20] is irreversible under the pyrolysis conditions. In the phenylcyclopropane case, restoration of the aromatic resonance could provide a means for reversing the rearrangement that is not available in the vinyl cyclopropane system.

In detail, however, this hypothesis is implausible, since in order to mimic the synchronous double rotation and produce clean two-center epimerization (**2**-*2-d* → **2'**-*2-d*, Scheme V), the mechanism would have to be restricted to one suprafacial-retention and one antarafacial-inversion 1,3-sigmatropic rearrangement, in either order. Any significant contribution from another stereochemical course (suprafacial-inversion or antarafacial-retention) would result in loss of the stereospecificity of the rearrangement. As several studies have shown,[21-23] antarafacial migrations are highly unfavorable in the 1,3-sigmatropic rearrangements of small-ring vinyl derivatives. Therefore, the vinylcyclopropane–phenylcyclopropane anomaly probably has a different origin.

Experimental Section

Authentic samples of C_9 hydrocarbons were prepared by standard methods and characterized by NMR spectroscopy. *n*-Propylbenzene (**5**) was prepared by Wolff–Kishner reducion of propiophenone; α-methylstyrene (**3**) by reaction of acetophenone with methyleneiriphenylphosphorane; a 10:90 mixture of *cis*- and *trans*-β-methylstyrene (**6**) by dehydration of 1-phenylpropanol (160 °C, H_2SO_4 catalyst) followed by GC separation of the hydrocarbons (see below). Allylbenzene (**7**) was a commercial sample.

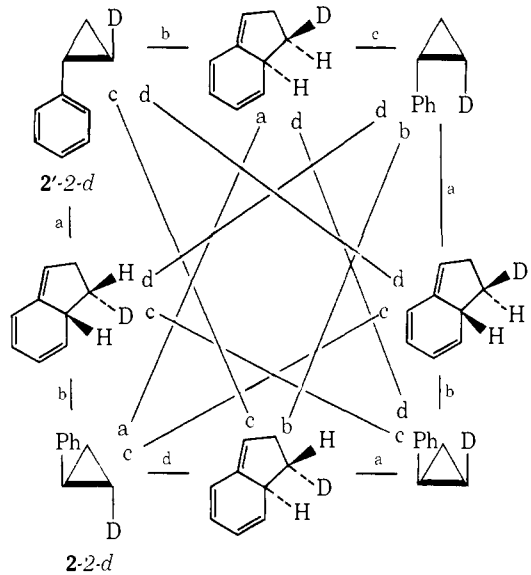
The GC columns used in this work follow: column A, 10 ft × 3/8 in. 20% Carbowax 20M on Chromosorb P, used at ~150 °C; column B, same as column A but 5 ft long; column C, 10 ft × 1/4 in. 20% dinonyl phthalate on Chromosorb W, used at 105–120 °C; column D, 20 ft × 1/8 in. Poropak Q; column E, 3% OV-17 on Anakrom ABS; column F, same as E, on Anakrom Q; column G, 3% OV-225 on Anakrom Q; column H, 3% Carbowax 20M on Anakrom AS; column I, 20% Carbowax 20M on Anakrom Q; column J, 3% SE-30 on Anakrom Q. Columns E–J were all 12 ft × 1/8 in. Columns A–C were used in the Varian 90-P instrument with thermal conductivity detection. Columns D–J were used in the Perkin-Elmer 900 instrument with flame ionization detection.

Optical rotations were measured as described previously.[3] Infrared spectra were recorded on a Beckman Model 4250 instrument using a cell with 0.027-mm path length and NaCl windows. Mass spectra were recorded on a Hitachi Perkin-Elmer RMU-6 instrument. NMR spectra were recorded with the Perkin-Elmer R-32 90-MHz or Bruker Supercon 270-MHz instrument.

Pyrolyses of 200–500-μL samples of phenylcyclopropane in ammonia-rinsed sealed ampules used the procedures previously described.[3]

The structural isomerization at 339 °C was examined by separation of the products with column B after a 46-h pyrolysis. This column did not separate all the components, but the four peaks observed corresponded in retention time to phenylcyclopropane (19.0 min), allylbenzene (10.7 min), *trans*-β-methylsytrene (18.4 min), and α-methylstyrene (14.3 min). The 10.7- and 18.4-min peaks were identified as corresponding to essentially pure allylbenzene and *trans*-β-methylstyrene by infrared analysis, but the 14.3-min peak showed only a minor absorption at 895 cm^{-1}, where α-methylstyrene absorbs strongly. Calibration of this absorption with a known concentration of an authentic sample permitted the conclusion that α-methylstyrene could not constitute more than 0.25% of the product mixture.

Scheme V[a]



[a] Each line represents a reversible pathway using one of the following 1,3-sigmatropic rearrangements: (a) antarafacial-inversion; (b) suprafacial-retention; (c) suprafacial-inversion; (d) antarafacial-retention. To achieve two-center epimerization, e.g., **2'**-*2-d* → **2**-*2-d*, it is necessary to invoke successive antarafacial-inversion and suprafacial-retention pathways, in either order.

Several similar pyrolyses at temperatures of 350–360 °C gave the product mixtures described in the text. Material balances of >90% were established, using ethylbenzene as an internal standard. The product compositions did not change appreciably in runs of 13–50 h, although some polymerization became evident at the longer reaction times, and the material balance fell to about 65–70%. Neither the product composition nor the rate was appreciably affected by the use of untreated, acid-washed, or base-washed ampules, or by packing the pyrolysis ampule with glass wool. The compounds of major interest here, *trans*- and *cis*-β-methylstyrene, allylbenzene, propylbenzene, and α-methylstyrene, all were analytically separated by column D. Under conditions where α-methylstyrene could have been detected at 0.1% of the mixture, none was observed. The other four products were preparatively separated with column C and identified by 270-MHz NMR comparison with authentic samples. The observed resonances in δ units, multiplicities, approximate coupling constants, integrations, and assignments of these spectra follow. **Allylbenzene:** 3.36 (d, $J \simeq 6$ Hz, 2 H, $-CH_2$), near 5.00 (m, 2 H, $=CH_2$), near 5.9 (m, 1 H, =CH), near 7.2 (m, 5 H, Ph). **Propylbenzene:** 1.00 (t, $J \simeq 7$ Hz, 3 H, CH_3), 1.71 (six-line pattern, 2 H, CH_2CH_3), 2.64 (t, $J \simeq 7$ Hz, 2 H, $PhCH_2$), near 7.2 (Ph). ***cis*-β-Methylstyrene:** 1.95 (d, $J \simeq 7$ Hz, 3 H, CH_3), 5.80 (m, 1 H, $=CHCH_3$), 6.45 (d, $J \simeq 10$ Hz, 1 H, PhCH=), 7.2 (m, 5 H, Ph). ***trans*-β-Methylsytrene:** 1.93 (d, $J \simeq 7$ Hz, 3 H, CH_3), 6.32 (m, 1 H, $=CHCH_3$), 6.47 (d, $J \simeq 16$ Hz, 1 H, PhCH=), 7.3 (m, 5 H, Ph).

Syntheses of Labeled Phenylcyclopropane-*2,3-d*$_2$ Stereoisomers. The Syn-Cis Isomer (11, Scheme III). Phenylacetylene (Aldrich) was distilled from CaH_2 at 24 °C and 3–5 Torr. A 50.0-mL sample was added slowly to a filtered ether solution of EtMgBr (prepared from 35 mL of EtBr and 12 g of Mg in 150 mL of Et_2O) under nitrogen. After 10 h at reflux, 20 mL of D_2O was added. The mixture was extracted with pentane, dried over $MgSO_4$, filtered, and concentrated. The product phenylacetylene-d_1, 40 mL, 80% yield, distilled at 24 °C (3 Torr). The terminal acetylenic ^1H NMR resonance of the undeuterated compound could not be detected.

In a representative run, a reaction flask equipped to receive diisobutylaluminum hydride (Ethyl Corp.) was flame dried under N_2 and charged with 41.37 g of $(i\text{-}Bu)_2AlH$. Hexane (50 mL), which had been distilled from CaH_2, was added, and the solution was slowly treated with 28 mL of phenylacetylene-d_1. The mixture turned from yellow to deep red during 6 h at 50 °C, whereupon the contents of the flask was added to a mixture of 20 mL of H_2O and 200 mL of pentane.

The yellow slurry was filtered to remove aluminum salts, the filter cake was washed with three 50-mL portions of ether, and the combined filtrate and washings were dried over $MgSO_4$. Evaporation of the solvent and distillation of the residue at 24 °C (5 Torr) gave 26 mL of a mixture of 80% of *cis*-β-deuteriostyrene (**11**) and 20% of phenylacetylene (74% yield, corrected for recovered phenylacetylene, GC analysis). The styrene NMR spectrum showed resonances at δ 5.65 (d, 1 H, =C*H*D), 6.67 (d × t, 1 H, PhC*H*=), and 7.32 (m, 5 H, Ph).

A mixture of 4.0 g of cuprous triflate[15] and 70 mL of an 80:20 mixture of *cis*-β-deuteriostyrene and phenylacetylene under nitrogen was cooled to 0 °C and treated dropwise with a mixture of 15 mL of ethyl diazoacetate and 15 mL of the 80:20 hydrocarbon mixture. The mixture was allowed to warm to room temperature, stirred for 8 h, and treated with 100 mL of a pH 9 NH_4Cl/NH_3 solution. Extraction with ether, drying over $MgSO_4$, and distillation at 110–120 °C at 1–3 Torr gave an 83% yield of the mixed 2-phenylcyclopropane-1-carboxylic esters **8** (corrected for recovered olefin).

Hydrolysis[24] of the esters (20.8 g) with a boiling mixture of 8.0 mL of water, 60 mL of ethanol, and 6.45 g of NaOH for 9 h, followed by evaporation of the ethanol, gave a solid, which, after having been washed with ether, was dissolved in a minimum amount of water. The solution was washed with pentane and acidified with 20 mL of concentrated HCl, to give an oil which slowly solidified. Recrystallization from water gave the pure trans acid, mp 92.5–93 °C.

A dried sample of 16 g of this acid was dissolved in 200 mL of anhydrous ether and treated dropwise with 475 mL of 0.505 M ether solution of phenyllithium (20% excess over the required 2 equiv). The mixture was stirred for an additional 20 min and then was poured into 600 mL of 3 N aqueous NH_4Cl with rapid stirring. The organic layer was washed with saturated brine, dried over $MgSO_4$, and evaporated to dryness. The residue consisted of a mixture of the desired ketone **9**, bromobenzene, and biphenyl. The two contaminants were removed by heating the sample in a Kugelrohr at 70 °C (5 Torr). The yield of **9** was 13.6 g (65%).

The second deuterium label was incorporated by exchange with ethanol-*O*-*d*. A solution of KOEt was prepared from 1 g of potassium metal and 25 mL of EtOD and diluted volume for volume with 1,2-dimethoxyethane which had been distilled from CaH_2. This solution was added to a solution of 5 g of ketone **9** in 10 mL of EtOD, using a glovebag under N_2 atmosphere. The mixture was heated at reflux for 3 h, cooled, and treated with 10 mL of D_2O. After having been stirred for 10 min under N_2, the brown solution was extracted with ether. The ether layer was washed with brine, dried over $MgSO_4$, and evaporated to give the dideuterio ketone **10**.

The Haller–Bauer cleavage of 4 g of **10** in 100 mL of dry benzene was effected by treatment of the solution, under N_2, with 3.0 g of $NaNH_2$ and heating the mixture at reflux for 2 h. After the cautious addition of 10 mL of water the mixture was poured into 100 mL of water and extracted with four 20-mL portions of pentane. The organic layer was dried and distilled. The fraction with bp 30–40 °C (3 Torr) was purified by preparative GC on column A. A sample of this material mixed with authentic phenylcyclopropane gave one peak on GC columns A, E, F, and I. The NMR showed resonances at δ 7.11 (m, 5 H, Ph), 1.79 (t, 1 H, PhC*H*), 0.85 (d, 2 H, anti C_2–C_3). The integration of the syn-cis region (δ 0.6–0.7)[3b,25] showed 85% incorporation of two deuteriums at C_2 and C_3 cis to the phenyl group. The mass spectrum at 15.5 eV showed this sample to consist of 0.7% d_0, 13.6% d_1, 74.8 d_2, and 10.9% d_3.

The anti-cis isomer (14, Scheme IV) was obtained by a similar sequence, except for two features. First, ordinary (not deuterated) phenylacetylene was subjected to hydroalumination, and the workup used D_2O instead of H_2O to quench the reaction mixture. Second, the Haller–Bauer cleavage of **13** used $NaND_2$ (Merck of Canada) instead of $NaNH_2$. The anti-trans hydrocarbon **14**, after GC purification on column A, showed resonances at δ 7.10 (m, 5 H, Ph), 1.81 (br t, 1 H, PhC*H*), 0.64 (d, 2 H, C_2–C_3 protons syn to Ph). The mass spectrum at 15.5 eV showed 4.9% d_0, 34.2% d_1, 55.7% d_2, and 5.2% d_3.

Resolution of *trans*-2-phenylcyclopropane-*cis*-1-carboxylic acid-*cis*-3-*d* (**12**, Scheme IV) was achieved by a modification of the methods reported elsewhere.[3,19] After two recrystallizations of the quinine salt from ethyl acetate, the acid recovered had $[\alpha]_D$ + 190°, but attempts to complete the resolution with dehydroabietylamine[3] were unsatisfactory, because the rotation of the acid recovered from the salt had decreased. Accordingly, the recovered acid (15.2 g) was converted to the brucine salt, which crystallized from acetone. The crystals were dissolved in the minimum amounts of warm acetone, cooled to 0 °C, and brought to slightly acidic pH by dropwise addition of concentrated HCl. Ice water was added until the solid dissolved, the acetone was removed with a rotary evaporator, and cold dilute HCl was added until no further crystallization occurred. The crystals were filtered and dried to give 2 g of acid, $[\alpha]_D$ −324°. The mother liquors upon concentration to half their volume and dilution with dilute HCl gave 4.6 g of material with $[\alpha]_D$ +352° ($CHCl_3$).

Optically Active Phenylcyclopropane-2,3-d_2 (15). Synthesis of phenylcyclopropane from the active (+) acid followed the same procedures described in the preceding paragraphs and outlined in Scheme IV. The final Haller–Bauer cleavage with $NaNH_2$ in benzene gave a 55% yield of a colorless liquid hydrocarbon. After GC purification on column A, (+)-**15** showed α^5_D +0.519° (neat, 0.5 dm); NMR δ 7.11 (m, 5 H, Ph), 1.80 (br t, 1 H, PhC*H*), 0.87 (d × t, 2 H, C*H*D). The mass spectrum at 15.5 eV showed 1.4% d_0, 19.3% d_1, 74.0% d_2, and 5.4% d_3.

Gas-phase pyrolysis of eight separate 150-μL portions of (+)-**15** at 309.5 °C and approximately 1 atm were carried out in sealed Pyrex ampules for periods ranging from 6000 to 72 000 s. After pyrolysis, each sample was purified by preparative GC on column A and the optical rotation was measured in a 0.5-dm tube. Figure 1 presents the data.

References and Notes

(1) Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this work. We also thank the National Science Foundation (CHE-76-00416) for partial support. We wish to acknowledge the support of the Southern New England High Field NMR Facility made possible by a grant from the Biotechnology Resources Program of the National Institutes of Health (RR-798).
(2) J. A. Berson and L. D. Pedersen, *J. Am. Chem. Soc.*, **97**, 238 (1975).
(3) (a) J. A. Berson, L. D. Pedersen, and B. K. Carpenter, *J. Am. Chem. Soc.*, **97**, 240 (1975); (b) *ibid.*, **98**, 122 (1976).
(4) For a review of cyclopropane stereomutations, see J. A. Berson, *Annu. Rev. Phys. Chem.*, **28**, 111 (1977), and references cited therein.
(5) H. E. O'Neal and S. W. Benson, *J. Phys. Chem.*, **72**, 1866 (1968).
(6) S. W. Benson, "Thermochemical Kinetics", Wiley, New York, N.Y., 1976.
(7) A. Gavezzotti and M. Simonetta, *Tetrahedron Lett.*, 4155 (1975).
(8) P. A. Leermakers and M. E. Ross, *J. Org. Chem.*, **31**, 301 (1966).
(9) M. R. Willcott, R. L. Cargill, and A. B. Sears, *Prog. Phys. Org. Chem.*, **9**, 25 (1972).
(10) H. M. Frey and R. Walsh, *Chem. Rev.*, **69**, 103 (1969).
(11) H. E. O'Neal and S. W. Benson, *J. Phys. Chem.*, **72**, 1866 (1968).
(12) S. W. Benson and H. E. O'Neal, "Kinetic Data on Gas Phase Unimolecular Reactions", NSRDS-NBS 21, National Bureau of Standards, Washington, D.C.
(13) R. G. Bergman in "Free Radicals", Vol. I, J. Kochi, Ed., Wiley, New York, N.Y., 1973, p 191.
(14) We cannot claim to have established the presence of indene with certainty and therefore do not challenge the report[8] of its absence.
(15) Cf. G. Zweifel and R. B. Steele, *J. Am. Chem. Soc.*, **89**, 2753 (1967).
(16) R. G. Salomon and J. K. Kochi, *J. Am. Chem. Soc.*, **95**, 3300 (1973).
(17) F. J. Impastato and H. M. Walborsky, *J. Am. Chem. Soc.*, **84**, 4838 (1962).
(18) C. L. Bumgardner and K. G. McDaniel, *J. Am. Chem. Soc.*, **91**, 6821 (1969).
(19) Y. Inouye, T. Sugita, and H. M. Walborsky, *Tetrahedron*, **20**, 1695 (1964).
(20) M. R. Willcott, III, and V. H. Cargle, *J. Am. Chem. Soc.*, **91**, 4310 (1969).
(21) J. A. Berson and P. B. Dervan, *J. Am. Chem. Soc.*, **95**, 267 (1973).
(22) J. A. Berson, P. B. Dervan, R. Malherbe, and J. Jenkins, *J. Am. Chem. Soc.*, **98**, 5937 (1976).
(23) J. E. Baldwin and K. E. Gilbert, *J. Am. Chem. Soc.*, **98**, 8283 (1976).
(24) A. Burger and W. L. Yost, *J. Am. Chem. Soc.*, **70**, 2198 (1948).
(25) K. B. Wiberg, D. E. Barth, and P. H. Schertler, *J. Org. Chem.*, **38**, 378 (1973).