Tetrahedron, Vol. 37, Supplement No. 1, pp. 329 to 344, 1981
Printed in Great Britain

0040–4020/81/Suppl. 1–0329–16 $02.00/0
Pergamon Press Ltd.

CONSTITUTIONAL AND CONFIGURATIONAL ASPECTS OF THE THERMAL REORGANIZATION OF 1-CYANO-2-VINYLCYCLOBUTANE (I)

W. VON E. DOERING* and A. R. MASTROCOLA

Department of Chemistry, Harvard University, Cambridge, MA 02138, U.S.A.

(*Received in U.S.A.* 21 *July* 1980)

Abstract—Kinetics and Arrhenius parameters have been determined for three processes: automerization, ring expansion and cycloreversion, occurring in the thermal reorganization of racemic *cis* and *trans*-I. Through the reorganization of optically active materials, automerization is trisected into enantiomerization and two epimeric diastereomerizations, and ring expansion is dissected into processes leading to enantiomeric 4-cyanocyclohexenes (II). Evidence pointing to concertedness being undiscernible, the system of reorganizations is classified as not obviously concerted and discussed in terms of relative propensities of groups to rotate internally. Comparison with similar cyclopropane systems reveals no qualitative differences (beyond cycloreversion) and only one substantial quantitative difference; that is, an enhanced tendency in the cyclobutane toward ring expansion.

In order better to understand the role of internal rotation in thermal rearrangements of small rings, the behaviour of *cis* and *trans* 1-cyano-2-vinylcyclobutane (*cis*- and *trans*-I; Fig. 1)[1] is investigated. The purpose is to compare 3- and 4-membered rings in diastereomerization and enantiomerization (Fig. 1) and in ring expansions, to cyclopentene and cyclohexene, respectively (Fig. 2).

In studies of 1-cyano-2-isopropenylcyclopropane (Fig. 1: $H_m = CH_3$, cyclopropane *vice* cyclobutane; Table 5, *vide infra*), relative rotational propensities have been recognized as the key factor.[2] From the proof of Onsager that the product of specific rate constants in one sense is equal to the product in the opposite sense in a multicomponent system at equilibrium,[3] it follows specifically in the case in Fig. 1 that $k_1k_4k_1k_4 = k_2k_3k_2k_3$ whence the ratio $k_4/k_3 = k_2/k_1$. This ratio (R_A) defines the relative propensity of A to rotate internally in preference to B and is independent of starting material (k_4/k_3 from *cis* and

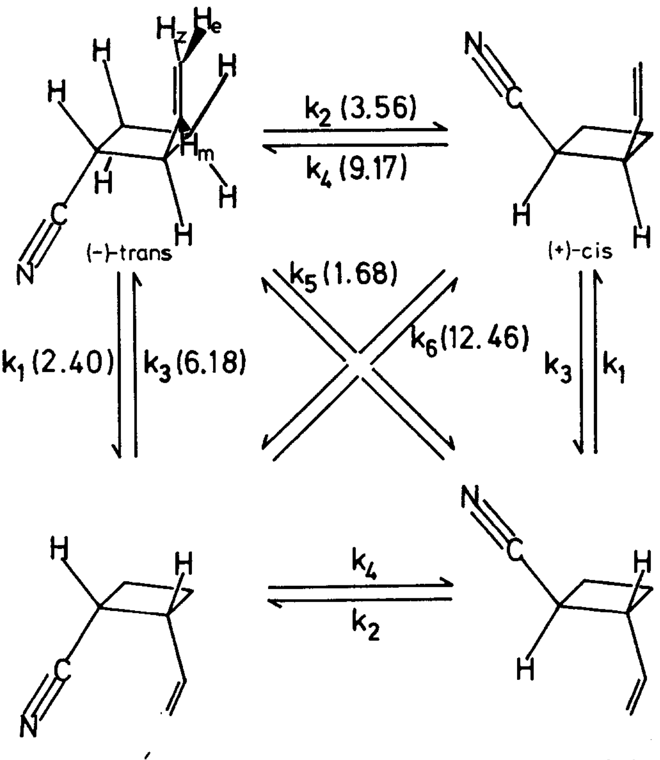


Fig. 1. Diastereomerization and enantiomerization (automerization) in 1-cyano-2-vinylcyclobutane (I) (specific rate constants at 217.8°, 10^{-6} sec^{-1}).

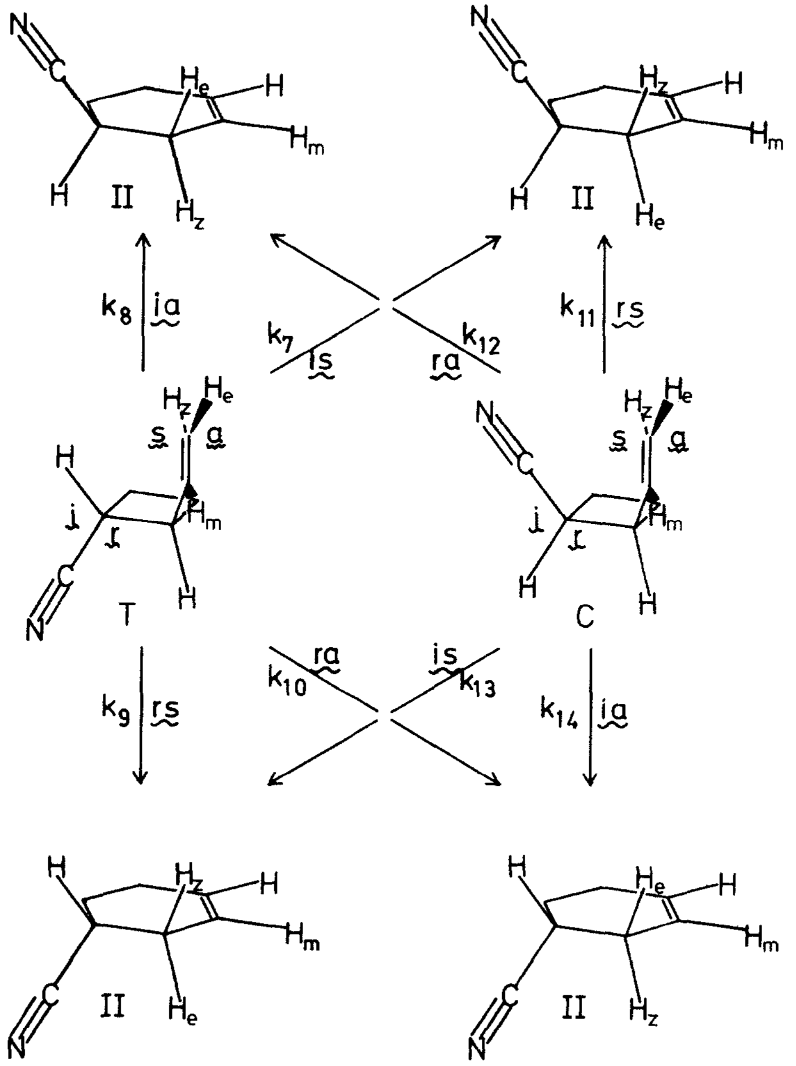


Fig. 2. The scheme of Mazzocchi and Tamburin[6] for the stereochemical elucidation of ring expansion is illustrated with 1-cyano-2-vinylcyclobutane (I). Values of specific rate constants at 217.8 follow: $(k_7 + k_8) = k_{\mathrm{TIIi}} = 2.90$, $(k_9 + k_{10}) = k_{\mathrm{TIIr}} = 2.07$; $(k_{11} + k_{12}) = k_{\mathrm{CIIr}} = 4.47$ and $(k_{13} + k_{14}) = K_{\mathrm{CIIi}} = 2.12 \times 10^{-6}\,\mathrm{sec}^{-1}$.

k_2/k_1 from *trans*). In 1-cyano-2-isopropenylcyclopropane at 217.8°, rotation of A (cyano) is favored over rotation of B (isopropenyl) by a factor of 2.20.

Ring expansion in this cyclopropane series (Fig. 2: $H_m = CH_3$, cyclopropane → cyclopentene; Table 5, *vide infra*) is barely competitive: 2.50% from the *trans* isomer, 1.17% from the *cis* isomer. Because the terminal CH_2 moiety of the vinyl group is unsubstituted, stereochemical analysis is limited to inversional (**i**) and retentional (**r**) components and cannot inform the suprafacial (**s**) and antarafacial (**a**) components. Determined from the *trans* isomer, the ratio, **i**/**r**, is 2.4; from the *cis* isomer, **i**/**r** = 0.67.[4]

Related to this work are examples of Berson *et al.*[5] of cyclobutanes *cis*- and *trans*-1,2-disubstituted by *cis*- and *trans*-propenyl groups (Fig. 2: H_e or $H_z = CH_3$; $CH_3CH{=}CH-$ vice CN). Designed to probe other aspects of the multifaceted mechanistic problem, the two more thoroughly studied examples contain sufficient symmetry to confer achirality on the *cis* diastereomers and therefore have an R_A factor equal trivially to 1.00. However insufficient to realization of the full potential in the Mazzocchi–Tamburin design,[6] shown in Fig. 2, they permit elucidation of the stereochemistry of the ring expansion from the *trans* isomer. Such a limitation does not apply to the *cis* and *trans* 1-*cis*-propenyl-2-*trans*-propenylcyclobutanes, examples which, quite understandably, remain incompletely investigated.

The present work, too, falls short of a theoretically full elucidation owing to lack of labelling in the vinyl group. It does permit evaluation of an R_A factor, which reasonably can be compared with that of the closely related cyclopropane,[2] and it does allow determination of the inversional (**i**) and retentional (**r**) (but not the suprafacial (**s**) and antarafacial (**a**)) components of

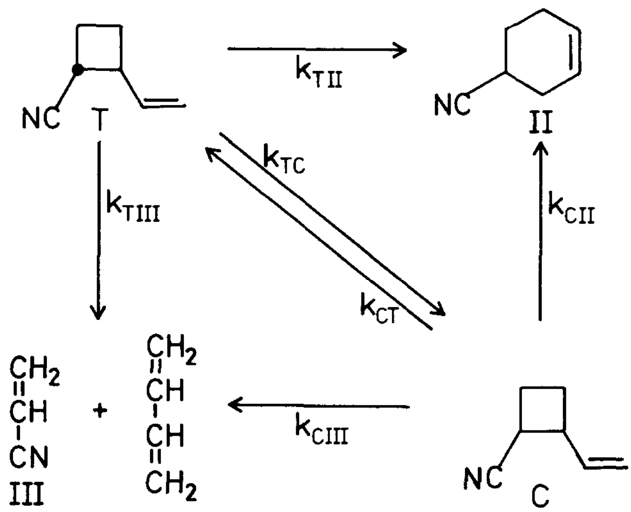


Fig. 3. These competitive constitutional reorganizations constitute the minimal kinetic set for *racemic* 1-cyano-2-vinylcyclobutane. With reference to Fig. 1, $(k_1 + k_2) = k_{TC}$ and $(k_3 + k_4) = k_{CT}$; and with reference to figure 2, $(k_7 + k_8 + k_9 + k_{10}) = k_{TII}$ and $(k_{11} + k_{12} + k_{13} + k_{14}) = k_{CII}$.

the ring expansion of both the *cis* and *trans* diastereomers for comparison with their close cyclopropane relatives.[4]

Although full Mazzocchi–Tamburin design has by now been realized in the cyclopropane series by Doering and Barsa,[7] in the cyclobutane series a similarly complete treatment awaits the completion of current studies of *cis*- and *trans*-1-cyano-*trans*-propenylcyclobutane (also labelled stereospecifically with deuterium in the 3 and 4 positions to permit resolution of the internal rotational components of cycloreversion[8]).

Kinetics of thermal reactions of racemic cis *and* trans-1-*cyano-2-vinylcyclobutane*

cis-I and *trans*-I are prepared by the photosensitized cycloaddition of butadiene and acrylonitrile according to the method of Dilling and Kroening.[9] When heated in the gas-phase at 217.8°, *cis*-I and *trans*-I undergo the reactions outlined in Fig. 3 with a mass balance >98% of theory.

Within the limits of detection (~0.2%), 3-cyanocyclohexene, which might have resulted from breaking the C_2–C_3 bond, is not formed. 4-Cyanocyclohexene (II) is recovered unchanged on being heated to 217.8° for 12 hr.

Various factors which might have influenced the rearrangements of I are collected in Table 1. Because changing from Pyrex, an acidic glass, to Corning 0120, a basic lead-potash glass, makes no difference, surface catalysis is not indicated. The lack of change between experiments at 700 mm and 1 mm total pressure indicates that results pertain to the high-pressure region, as would be expected according to RRKM

Table 1. Thermal rearrangement of I under a variety of conditions for 4 hr at 217.8°

Conditions	Products						
	cis-I		trans-I		II		III
	yield,%	opt.pur.,%	yield,%	opt.pur.,%	yield,%	opt.pur.,%	yield,%
700 mm/Pyrex[a]	64.7	69.3	15.9	13.7	8.3	23.5	11.1
700 mm/0120[a,c]	64.6	----	14.9	----	8.0	----	12.5
1 mm/Pyrex[a]	69.1	68.1	16.3	13.4	8.3	23.9	6.3
CH_3CN (10% sol.)[a]	60.7	81.1	10.1	9.4	12.7	13.2	16.4
700 mm/Pyrex[b]	6.2	14.6	81.2	94.4	6.7	14.4	5.9
700 mm/0120[b,c]	5.9	----	81.2	----	6.6	----	6.2
CH_3CN (10% sol.)[b]	5.2	10.1	78.2	95.9	10.0	2.1	6.9
C_6H_6 (10% sol.)[b]	5.4	9.1	77.5	93.6	10.9	6.8	5.1

[a] Starting material is (+)-cis-I. When not 100% of optical purity, results are corrected. [b] Starting material is (+)-trans-I. Similarly corrected. [c] Corning 0120, lead-potash glass.

Table 2. Specific rate constants for the six thermal reorganizations of *cis*- and *trans*-I

k_i[a]	T°C	217.8°[b]	207.1°[b]	191.7°[c]	178.4°[d]
k_{TC}		5.96 ± 0.1 *5.87* ± *0.07*	2.28 ± 0.1 *2.25* ± *0.06*	4.54 ± 0.3 *4.45* ± *0.23*	11.92 ± 0.3 *12.01* ± *1.05*
k_{TII}[e]		4.95 ± 0.1 *4.93* ± *0.06*	1.89 ± 0.1 *1.87* ± *0.03*	4.52 ± 0.6 *3.88* ± *0.21*	10.31 ± 0.2 *10.48* ± *0.90*
k_{TIII}		4.16 ± 0.4 *4.16* ± *0.32*	1.58 ± 0.1 *1.57* ± *0.03*	3.00 ± 0.2 *2.99* ± *0.09*	7.35 ± 0.5 *7.43* ± *0.29*
k_{CT}		15.29 ± 0.2 *15.12* ± *0.28*	6.29 ± 0.1 *6.18* ± *0.10*	12.86 ± 0.6 *12.71* ± *0.66*	34.5 ± 0.3 *34.12* ± *0.26*
k_{CII}		6.60 ± 0.1 *6.51* ± *0.11*	2.66 ± 0.1 *2.64* ± *0.05*	5.32 ± 0.4 *5.26* ± *0.31*	14.19 ± 0.2 *14.10* ± *0.16*
k_{CIII}		8.64 ± 0.5 *8.55* ± *0.99*	3.44 ± 0.3 *3.39* ± *0.25*	6.49 ± 0.8 *6.40* ± *0.59*	15.70 ± 0.5 *15.59* ± *0.42*

[a] The six specific rate constants outlined in Figure 3. [b] k_i in units of 10^{-6} sec^{-1}. [c] k_i in units of 10^{-7} sec^{-1}. [d] k_i in units of 10^{-8} sec^{-1}. [e] Values in italics obtained by Glenn Graham.[15]

theory for molecules of this many atoms. The same conclusion may be drawn from the results in benzene. Acetonitrile as solvent reveals little effect on the rates of rearrangement or influence on product distribution and configurational characteristics. There is possibly a little less diastereomerization relative to ring enlargement and cleavage, but no sufficiently dramatic effect to suspect a change from homolytic to heterolytic mechanism of the type so convincingly demonstrated by Chmurny and Cram in more appropriately substituted cyclopropanes.[10]

The possibility that *trans*-I and II might be formed from *cis*-I by subsequent condensation of the primary decomposition products, acrylonitrile (III) and butadiene,[9] can be rejected. First, *trans*-I is produced from *cis*-I (and *vice versa*) in far too high an amount to be accommodated by the condensation, which leads to II, *cis*-I and *trans*-I in the ratios, 200:1:1, respectively.[11] Second, a quantitative estimate of the rate of condensation is too low to account for the amount of II formed from *cis*-I or *trans*-I. A single, specific rate constant, available for the Diels–Alder condensation of acrylonitrile and butadiene ($k_{ab} = 9 \times 10^{-6}$ l/m.s. at 120°), can be coupled with an estimated† $E_a = 20600$ cal/mol to generate an estimated set of parameters, $\log k_{ab} = 6.40 - 20600/RT\ln 10$ and thence an estimated $k_{ab} = 1.72 \times 10^{-3}$ l/ms. at 217.8°. If the longest run with *cis*-I at the highest temperature (14400 sec at 217.8°) is taken and the assumption is made that the 11.1 % of III and butadiene present at the end of the reaction had prevailed from the beginning, no more than 2.1 % of the total amount of II could have arisen by a secondary Diels–Alder condensation.†

For determination of specific rate constants, reactions are effected in Pyrex ampoules with benzonitrile added as an internal standard for the subsequent gc analyses. The data are collected in Table 6. Specific rate constants are computed by numerical integration until, by trial and error, differences between experimental and calculated concentrations of all components at each time have been minimized. The function minimized ($\bar{\sigma}$) corresponds to the standard deviation (σ) in linear regression, but does not have the same statistical significance, since best fits are being sought for curved lines. The following set of differential equations corresponds to the scheme in Figure 3 and is the model for the extraction of specific rate constants:

$$
\begin{aligned}
d[T]/dt &= -(k_{TC} + k_{TII} + k_{TIII})[T] + k_{CT}[C] \\
d[C]/dt &= -(k_{CT} + k_{CII} + k_{CIII})[C] + k_{TC}[T] \\
d[II]/dt &= k_{TII}[T] + k_{CII}[C] \\
d[III]/dt &= k_{TIII}[T] + k_{CIII}[C]
\end{aligned}
$$

For each of the four components, we have plotted $\bar{\sigma}_j$ vs each of the six specific rate constants, k_i. From the resultant "sensitivity" curves, an optimum value of k_i is easily identified. Uncertainty in k_i is arbitrarily taken as those + and − increments which lead to a doubling of the best $\bar{\sigma}_j$. The resultant ± values are certainly not standard deviation in the normal sense, but they should at least indicate relative uncertanties among k_i.[1] Optimized values for the six specific rate constants at four temperatures are recorded in Table 2.

The widely ignored problem of extracting uncertainties for systems of many specific rate

---

†Activation parameters for condensation of acrylonitrile–isoprene have been determined: $\log k = 6.75 + 19000/RT\ln 10$;[12] the difference in E_a between acrolein–isoprene ($\log k = 6.16 + 18700/RT\ln 10$) and acrolein–butadiene ($\log k = 6.01 + 19700/RT\ln 10$) is ~1000 cal/mol;[13] the ratio of k (acrolein)/k(acrylonitrile) = 7.9 in reactions with butadiene at 120° corresponds to $\Delta\Delta G^{\neq} \sim 1600$ cal/mol.[14]

†The ~6 mg of *cis*-I (m.w. 125.1) in an 8-ml ampoule in these runs corresponds to ~6.0×10^{-3} mol/liter. Setting the concentrations of III and butadiene at 11.1 % of this value, it can be calculated from the rate equation that 8.06×10^{-6} mol/liter of Diels–Alder condensation product would have been formed. This amounts to 2.1 % of that actually produced.

constants from the sum of the squares of the residual differences between calculated and observed concentrations has been examined by Glenn Graham.[15] The results of his application of the Simplex method to optimization of rate constants and of the theory of prediction error estimates to extract the associated standard deviations are also given in Table 2.

Arrhenius parameters are derived in the usual manner by least squares linear regression from the data in Table 2 and are collected in Table 3. The value of the equilibrium constant, $K = k_{CT}/k_{TC}$, is consistent with the small effective van der Waals circumference of the cyano group.[16] The interaction appears to originate in the enthalpy term: $\log K = (-0.126 \pm 0.18) + (1250 \pm 400)/RT\ln 10$.

Rates of disappearance of *trans*-I (k_T) and of *cis*-I (k_C) are given by the following expressions:

$$\log k_T = (14.82 \pm 0.16) - (44100 \pm 330)/RT\ln 10$$

$$\Delta H^{\pm} = 43.2\,\text{kcal/mol};\ \Delta S^{\pm} = 6.4\,\text{e.u.}$$

$$\log k_C = (14.91 \pm 0.39) - (43600 \pm 830)/RT\ln 10$$

$$\Delta H^{\pm} = 42.7\,\text{kcal/mol};\ \Delta S^{\pm} = 6.8\,\text{e.u.}$$

Question of concertedness

Three features of the kinetic results from racemic *cis*- and *trans*-1 are worthy of note. First, the two sets of three disparate reactions in Fig. 3, one each from *cis* and *trans*, encompass a narrow range of energies of activation (2.65 kcal/mol) and a narrow range of preexponential factors (1.23 in log A). Within each of the two sets of the ratio of the fastest to the slowest process is no greater than 2.3. Between the two sets the ratio of related rate constants is also small, but that is no more than a reflection of the remarkably small steric influence exercised by the cyano group.[16] Clearly, no extraordinary, fortuitously compensating effect on the entropy of activation conceals a process of widely differing enthalpy of activation.

Second, these thermal reorganizations can be related to the cycloreversion of unsubstituted cyclobutane by considering their respective enthalpies of activation, all of which are clustered between 41.9 and 44.6 kcal/mol. The best value[17] for cyclobutane we owe to Vreeland and Swinehart,[18] who deduce the rate expression, $\log k = 15.85 - 63200/RT\ln 10$, whence $\Delta H^{\neq} = 61.7$ kcal/mol and $\Delta S^{\neq} = 10.2$ e.u. If compensations for substitution of H by cyano[19] and vinyl[20] are made by subtraction of their stabilizing effects on the carbon free radical, 8 and 15 kcal/mol, respectively, a predicted value for the enthalpy of activation of 38.7 kcal/mol is derived. This model implies no greater a degree of concertedness than that contained in the reference reaction, cycloreversion of cyclobutane. Although it is widely accepted that cycloaddition/reversion is not concerted, strong support for this hypothesis is provided in a recent stereochemical study by Doering and Guyton of labelled acrylonitrile.[8] Consistently, the energy criterion of concert—that the experimental enthalpy of activation be lower, by an amount outside the estimated limits of uncertainty, than an enthalpy of activation, experimental or calculated as the case may be, associated with an appropriate non-concerted model—offers no encouragement for assigning either this reaction or its two relatives to the concerted class.

The third feature to note is the apparent absence of feedback of thermochemical information in the products to the respective transition states for their formation. Why are these thermal reorganizations so insensitive to the substantial thermochemical and constitutional differences among the three types of products? Heats of formation are known for acrylonitrile and butadiene,[21] but not for *cis*-I, *trans*-I or II. Although there are ample data supporting an increment, 32.87 kcal/mol, for the replacement of primary H in RH by CN,[22] there is only a single value for the replacement of secondary H by CN. We take that value, the difference between isopropylnitrile and propane, 31.01 kcal/mol,[21] as the basis for deriving the heat of formation of 4-cyanocyclohexene (II) from that of cyclohexene. The heat of formation of *trans*-I is estimated by adding to that of cyclobutane this increment for the replacement of secondary hydrogen by secondary nitrile and an increment for the replacement of secondary hydrogen by secondary

Table 3. Arrhenius parameters for the six thermal reorganizations of *cis*- and *trans*-1

k_i[a]	$\log A_i \pm s$	$\Delta S_i^{\neq}$	$E_{a_i} \pm s$	$\Delta H_i^{\neq}$
k_{TC}	14.41 ± 0.31	4.48	44.09 ± 0.66	43.15
k_{TII}	13.88 ± 0.38	2.08	43.08 ± 0.82	42.14
k_{TIII}	14.88 ± 0.31	6.66	45.50 ± 0.66	44.56
k_{CT}	14.27 ± 0.38	3.87	42.85 ± 0.82	41.91
k_{CII}	14.15 ± 0.38	3.29	43.39 ± 0.82	42.46
k_{CIII}	15.11 ± 0.42	7.71	45.28 ± 0.90	44.34

[a] $\log k_i = \log A_i - E_{a_i}/RT\ 10^{-3}\ln 10$; E_{a_i} and $\Delta H_i^{\neq}$ in kcal/mol; $\Delta S_i^{\neq}$ in cal/deg.

vinyl, 18.65 kcal/mol.† The heat of formation of *cis*-I is that of *trans*-I corrected by the experimental difference revealed in the temperature dependence of their equilibrium constant; i.e. 1.25 kcal/mol (*vide supra*).

The customary enthalpy diagram is then constructed in order to facilitate visualization of relations among heats of formation of stable molecules and interconnecting transition states (Fig. 4). Several features emerge.

Thermodynamically, ring enlargement is enthalpically favored by 26.5–27.7 kcal/mol over automerization, its closest competitor, and might be expected to generate II exclusively but, in fact, falls far short of doing so. In contrast, cycloreversion, also an operationally competitive process, is disfavored enthalpically by a significant amount, 13 ± 0.5 kcal/mol. To be sure, the thermodynamically controlled position of equilibrium is not unfavorable in the temperature range studied (178.4–217.8°), nor is it expected to be, because a favorable change in entropy of translation, a not unreasonable estimate of which is $\Delta S \sim 30$ e.u., could contribute 14 ± 0.5 kcal/mol. The third process, automerization, is essentially thermoneutral, because the full strain of the cyclobutane ring is reincorporated. It, too, competes effectively with the two other types.

Surely, the insouciance of rates to the inherent thermodynamic advantages and disadvantages of products must count as a striking aspect of these thermal reorganizations. This phenomenon appears to be a fundamental characteristic of the not obviously concerted class of reorganizations. Although more examples must be acquired if this presently tentative impression is to be transformed into a reliable empirical generalization, even now it must command close attention.

A conceptual device sufficient for blocking transmission of thermochemical information is the interposition of a hypothetical intermediate, the formation of which is rate-determining. More generally, it is necessary only that the reactions not be concerted, that the transition states, in the framework of orbital symmetry, either not be representable as resonance hybrids of educt and product or, if so representable, achieve no energy lowering thereby.

The Diels–Alder condensation of acrylonitrile and butadiene adds to the energy diagram a reaction widely regarded as concerted. While Arrhenius parameters for this reaction are not available, they can be estimated in reasonably reliable fashion and are given by the equation, $\log k_{ab} = 6.40 - 20600/RT\ln 10$ (*vide supra*). It is reassuring to note consistency with the reactions of butadiene with itself to give vinylcyclohexene [$\log k = 5.89 \pm 0.14) - (23060 \pm 290)/RT\ln 10$][23] and with ethylene to give cyclohexene [$\log k = (10.46 \pm 0.29) - (27500 \pm 800)/RT\ln 10$].[24]

The transition state of the Diels–Alder reaction of acrylonitrile and butadiene may thus be placed 8–11 kcal/mol below the other transition states of Fig. 4. This Diels–Alder reaction is thereby safely concerted by the criterion that the activation enthalpy be lower than that of a non-concerted model.

More nearly direct experimental confirmation of the degree of concert may be derived from the data of Dilling and Kroening,[9] who find ratios of 4-cyanocyclohexene to *cis*- and *trans*-I of 370 and 475, respectively, in the condensation of acrylonitrile and butadiene at 150° (no solvent). These ratios correspond to $\Delta\Delta G^{\neq}$ of 5.0 and 5.2 kcal/mol, respectively. Lack of data at other temperatures, however, prevents dissection into $\Delta\Delta S^{\neq}$ and $\Delta\Delta H^{\neq}$ or quantitative comparison with the value of $\Delta\Delta H^{\neq}$ indicated in Fig. 4 from the decomposition of *cis*- and *trans*-I.

Parenthetically, note that the corresponding lowering in the Diels–Alder dimerization of butadiene amounts to 3–4 kcal/mol.[23] Presumably, the greater radical-stabilizing effect of vinyl *vis-à-vis* cyano (15 vs 8 kcal/mol, respectively)[19] opposed by a slightly greater conjugative interaction in butadiene *vis-à-vis* acrylonitrile (3.5 vs 2.5 kcal/mol, respectively) suffices to account for the smaller, just barely recognizable degree of concert: 8–11 kcal/mol (concert with acrylonitrile) less 7 kcal/mol plus 1 kcal/mol equals 2–5 kcal/mol (concert with butadiene).

Qualities usually associated with concerted reactions—regiospecificity rather than multiplicity of products, lowered activation enthalpy *vis-à-vis* that predicted of a non-concerted model—are not evident in the thermal reorganizations of *cis*- and *trans*-I. Although their non-concerted nature should not be considered proved—if the non-existence of a quality be at all a fit subject for disproof—at least none of the reactions falls obviously into the concerted category. To assign this set of constitutionally disparate thermal reorganizations to the class of not obviously concerted transformations seems apt.

Optical activity in cis- *and* trans-*I*

Introduction of optical activity offers a further look into the thermal behaviour of *cis*- and *trans*-I. Although it sheds no light on cycloreversion, it illuminates the process of ring expansion, if only partially because optical activity must be coupled with additional constitutional labelling in the vinyl groups. (Fig. 2, $H_e = CH_3$, for example). However, the *cis* diastereomer, which is achiral in the published examples,[5] is chiral here. Having optical activity in both *cis*-I and *trans*-I promises the same degree of insight into automerization as has been obtained in closely related cyclopropanes.[2] For the first time, internal rotational propensity can be determined in a cyclobutane ring and compared with its counterpart in a cyclopropane ring. What can be expected of optical activity as a tracer is shown in Fig. 1 for automerization and in Fig. 2 for ring expansion. Owing to the equality of H_e and H_z, the number of distinguishable rate constants is reduced by a factor of 2: thus, $(k_7 + k_8) = k_{THi}$; $(k_9 + k_{10}) = k_{THr}$; $(k_{11} + k_{12}) = k_{CHr}$ and $(k_{13} + k_{14}) = k_{CHi}$.

The preparation of optically active *cis*-I and *trans*-I begins with the readily available *trans*-1,2-cyclobutanedicarboxylic acid[25] and proceeds to the corresponding monomethyl ester by way of the dimethyl ester.[26] Reduction by the action of diborane[26] followed by oxidation with the triethyl-

---

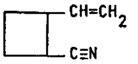
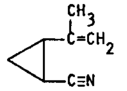
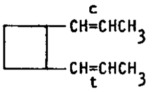
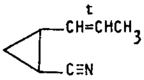
†The average of four differences in heats of formation obtained from the following pairs: 3-methylbut-1-ene–propane, 3-methylpent-1-ene–butane, vinylcyclopentane–cyclopentane and vinylcyclohexane–cyclohexane.[21]

Table 4. Specific rate constants at 217.8 of the reactions of (−)-*trans*-I and (+)-*cis*-I

(−)-trans-I		(+)-cis-I	
k_1[a]	2.40 ± 0.02[a,b]	k_3	6.18 ± 0.06
k_2	3.56 ± 0.05	k_4	9.17 ± 0.09
k_5	1.68 ± 0.28	k_6	12.46 ± 0.18
k_{TII_i}[c]	2.90 ± 0.03	k_{CII_i}	2.12 ± 0.06
k_{TII_r}	2.07 ± 0.02	k_{CII_r}	4.47 ± 0.06
k_{TIII}	4.17 ± 0.41	k_{CIII}	8.66 ± 0.55

[a] Error shown is $\pm 2\bar{\sigma}$ where $\bar{\sigma}$ is the square root of the sums of the squares of the deviations divided by n − 1. [b] Specific rate constants in units of 10^{-6} sec^{-1}. [c] See figure 2 in which $K_7 + k_8 = k_{TII_i}$, $k_9 + k_{10} = k_{TII_r}$, $k_{13} + k_{14} = k_{CII_i}$, $k_{11} + k_{12} = k_{CII_r}$.

Table 5. Comparison of thermal rearrangements among 1-cyano-2-vinylcyclobutane (this work), 1-*cis*-propenyl-2-*trans*-propenylcyclobutane,[5] 1-cyano-2-isopropenylcyclopropane,[4] and 1-cyano-2-*trans*-propenylcyclopropane[7]

				
k_1[a,b]	2.40	3.16	7.20 [f]	5.69
R_A[c]	1.48	2.20		2.36
K[d]	2.58	2.67	9.31	1.47
k_5	1.68	7.03	5.30	9.84
k_6	12.46	9.20		10.73
k_7 (is)	} 2.90[e]	0.31[e]	6.58	0.231
k_8 (ia)			0.04	0.097
k_9 (rs)	} 2.07[e]	0.13[e]	6.29	0.048
k_{10} (ra)			0.32	0.057
k_{13} (is)	} 2.12[e]	0.55[e]		0.29
k_{14} (ia)			5.4[g] 29.0[h]	0.27
k_{11} (rs)	} 4.47[e]	0.84[e]		0.57
k_{12} (ra)				0.18
T°C	217.8°	217.8°	146.5°	207.1°

[a] All rate constants in units of 10^{-6} sec^{-1}. [b] Rate constants are defined in figures 1 and 2. [c] $R_A = k_2/k_1 = k_4/k_3$. [d] $K = k_3/k_1 = k_4/k_2$. [e] With reference to figure 2, $k_{TII_i} = k_7 + k_8$; $k_{TII_r} = k_9 + k_{10}$; $k_{CII_i} = k_{13} + k_{14}$; $k_{CII_r} = k_{11} + k_{12}$. [f] Because starting material is racemic, this rate constant is not k_1, but $k_1 + k_2$. [g] $k_{12} + k_{13}$ (ra + is): trans-V. [h] $k_{11} + k_{14}$ (rs + ia): cis-V.

amine-dimethylsulfoxide-sulfur trioxide system[27] affords the aldehydic ester, condensation of which with methylene triphenylphosphorane[28] produces a 9:1 mixture of *trans*- and *cis*-1-carbomethoxy-2-vinylcyclobutane. From the mixture of *trans* and *cis* carboxylic acid obtained upon hydrolysis, recrystallization of the quinine salt from ethanol and water affords the (−)-*trans* enantiomer.

Although a constant specific rotation is attained after six recrystallizations, a better check on optical purity is obtained by oxidation and methylation to (1R:2R)-(−)-*trans*-1,2-biscarbomethoxycyclobutane which is of known optical purity and absolute configuration.[5]

Conversion to (1R:2S)-(−)-*trans*-I is accomplished by sequential treatment with ethyl chloroformate,

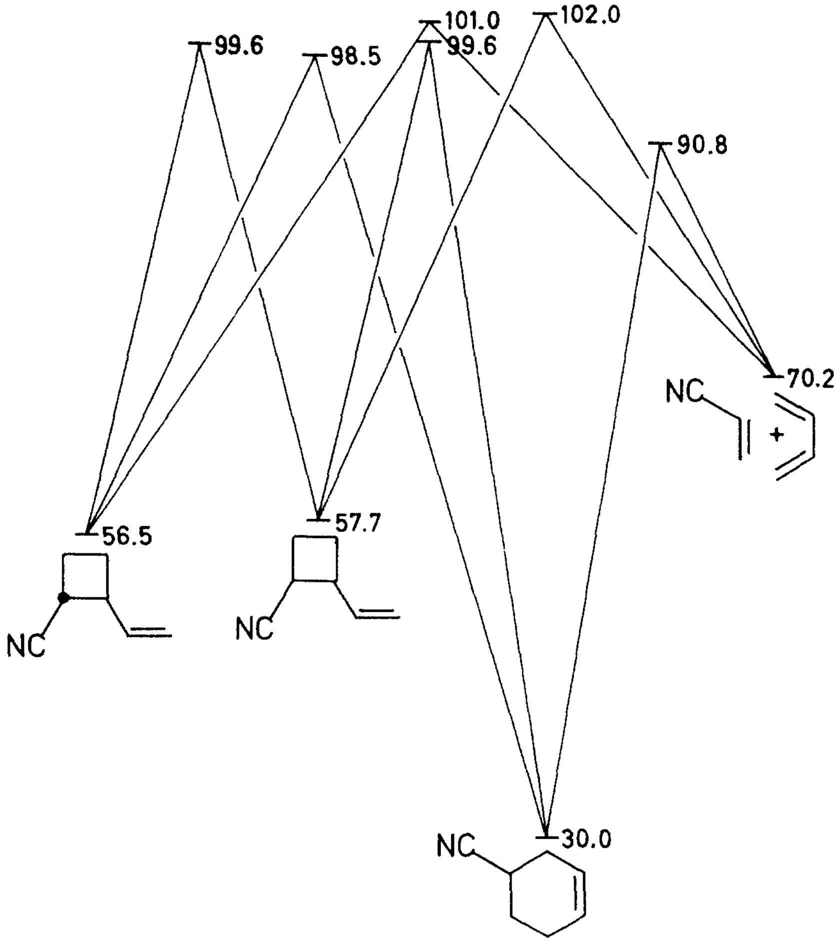


Fig. 4. Enthalpy diagram in kcal/mol (+) for reorganizations on the acrylonitrile-butadiene surface.

ammonia, and *p*-toluene sulfonylchloride in pyridine.[4] Owing to the unlikelihood of racemization in these reactions, the product, (−)-*trans*-I, is assumed to have the same degree of optical purity as the acid from which it is made.

Preparation of the *cis*-diastereomer of known optical purity and known configurational relation to (1R:2S)-(−)-*trans*-I is accomplished by establishment of equilibrium through the action of potassium t-butylate in dimethyl sulfoxide. Because recovered (−)-*trans*-I shows no decrease in specific rotation, and hydrogen α to cyano is known to be jeopardized under these conditions, it follows that (+)-*cis*-I and (−)-*trans*-I have the same configuration of the vinyl group and that (+)-*cis*-I is (1S:2S).

In order to complete the groundwork for the study, the maximum rotation of 4-cyanocyclohexene (II) and its configuration relative to I are required. The absolute configuration and maximum rotation of (S)-cyclohexene-4-carboxylic acid is already known by its chemical correlation to 4-vinylcyclohexene[29] and by the chemical correlation of 4-vinylcyclohexene to 3-methylcyclohexanone.[5] It thus remains only to convert (S)-(−)-cyclohexene-4-carboxylic acid to the corresponding nitrile, (S)-(−)-II by a conventional method. The absolute configurations are shown in Figs. 1 and 2, while maximum specific rotations are collected in Table 7.

Diastereomerization can be dissected into specific rate constants for the formation of each enantiomer: k_{TC} and k_{CT} of Fig. 3 into k_1 and k_2, and k_3 and k_4, respectively, of Fig. 1. Ring expansion can be dissected in similar fashion: k_{TII} and k_{CII} of Fig. 3 into k_{TII_i} and k_{TII_r}, and k_{CII_i} and k_{CII_r}, respectively, of Fig. 2. Additionally, enantiomerizations corresponding to the otherwise concealed reactions, k_5 and k_6, of Fig. 1 can be determined.

Quantitative evaluation of these rate constants is based on differential equations which represent cycloreversion and the transformations in Figs. 1 and 2 and define the concentrations of (+) and (−)-*cis* and *trans*-I, (+) and (−)-II and acrylonitrile (III). The experimental data are collected in Table 8. Note that treatment of optically active II at 217.8° for 12 hr occasions neither constitutional nor optical change. Approximate values of the specific rate constants for diastereomerization are obtained by graphical extrapolation to zero time of the fraction of retained optical activity at five different points and partitioning the specific rate constant for diastereomerization of

Table 6. Thermal reorganizations of I in Pyrex ampoules in the gas-phase[a]

Temp.[b] (°C)	Time (sec)	Trans-I[c] (%)	Cis-I[c] (%)	II[c] (%)	III[c] (%)	Recovery[d] (%)
217.8°[e]	2700	96.37 ± 0.23	1.49 ± 0.00	1.28 ± 0.01	0.86 ± 0.06	99.0
217.8°	5400	92.62 ± 0.48	2.83 ± 0.00	2.57 ± 0.02	1.96 ± 0.13	99.3
217.8°	8100	88.67 ± 0.19	4.01 ± 0.02	3.87 ± 0.02	3.43 ± 0.23	100.0
217.8°	10800	85.39 ± 0.24	5.04 ± 0.01	5.15 ± 0.02	4.41 ± 0.41	99.4
217.8°	14400	81.19 ± 0.24	6.17 ± 0.01	6.74 ± 0.02	5.90 ± 0.34	99.0
207.1°[f]	5400	96.96 ± 0.04	1.20 ± 0.01	0.97 ± 0.00	0.85 ± 0.05	100.0
207.1°	10800	93.98 ± 0.04	2.31 ± 0.02	1.95 ± 0.02	1.74 ± 0.04	99.0
207.1°	16200	91.37 ± 0.09	3.09 ± 0.01	2.95 ± 0.01	2.56 ± 0.10	99.9
207.1°	23400	87.80 ± 0.11	4.31 ± 0.02	4.27 ± 0.01	3.60 ± 0.12	100.0
207.1°	27000	86.12 ± 0.10	4.82 ± 0.02	4.90 ± 0.03	4.13 ± 0.10	99.9
191.7°[g]	21600	97.59 ± 0.03	0.91 ± 0.01	0.82 ± 0.01	0.66 ± 0.02	99.1
191.7°	43200	95.45 ± 0.06	1.71 ± 0.01	1.57 ± 0.01	1.25 ± 0.07	99.3
191.7°	64800	93.35 ± 0.06	2.45 ± 0.01	2.32 ± 0.01	1.86 ± 0.06	100.0
191.7°	86400	90.63 ± 0.19	3.37 ± 0.02	3.33 ± 0.02	2.61 ± 0.14	100.0
191.7°	108000	88.49 ± 0.11	4.09 ± 0.01	4.17 ± 0.00	3.20 ± 0.13	99.7
178.4°[h]	129600	96.36 ± 0.04	1.43 ± 0.00	1.30 ± 0.00	0.95 ± 0.04	99.5
178.4°	259200	92.82 ± 0.08	2.69 ± 0.02	2.57 ± 0.00	1.91 ± 0.10	99.7
178.4°	388800	89.56 ± 0.13	3.92 ± 0.02	3.94 ± 0.02	2.57 ± 0.17	99.4
178.4°	518400	86.44 ± 0.32	4.79 ± 0.06	5.09 ± 0.05	3.66 ± 0.37	100.0
178.4°	648000	83.08 ± 0.15	5.71 ± 0.02	6.40 ± 0.02	4.78 ± 0.19	99.5
217.8°[e]	2700	3.77 ± 0.01	92.99 ± 0.19	1.66 ± 0.01	1.57 ± 0.08	99.7
217.8°	5400	7.25 ± 0.01	85.57 ± 0.08	3.34 ± 0.02	3.85 ± 0.38	99.7
217.8°	8100	10.30 ± 0.02	78.82 ± 0.16	4.92 ± 0.04	5.95 ± 0.58	97.0
217.8°	10800	13.06 ± 0.20	72.06 ± 0.18	6.40 ± 0.03	8.46 ± 0.79	98.0
217.8°	14400	15.93 ± 0.03	64.70 ± 0.13	8.32 ± 0.00	11.05 ± 0.64	98.1
207.1°[f]	5400	3.05 ± 0.01	93.89 ± 0.03	1.31 ± 0.01	1.73 ± 0.03	99.7
207.1°	10800	6.17 ± 0.07	88.08 ± 0.33	2.74 ± 0.02	2.98 ± 0.43	99.5
207.1°	16200	8.70 ± 0.04	82.02 ± 0.33	4.01 ± 0.01	5.25 ± 0.36	100.0
207.1°	21600	11.19 ± 0.02	76.74 ± 0.41	5.32 ± 0.01	6.73 ± 0.44	100.0
207.1°	27000	13.18 ± 0.05	72.10 ± 0.16	6.46 ± 0.00	8.24 ± 0.15	99.8
191.7°[g]	21600	2.63 ± 0.00	95.02 ± 0.04	1.09 ± 0.01	1.25 ± 0.04	99.0
191.7°	43200	5.12 ± 0.01	90.22 ± 0.08	2.09 ± 0.01	2.54 ± 0.09	100.0
191.7°	64800	6.94 ± 0.03	86.45 ± 0.16	3.08 ± 0.03	3.51 ± 0.20	100.0
191.7°	86400	9.64 ± 0.02	80.63 ± 0.06	4.38 ± 0.02	5.33 ± 0.08	100.0
191.7°	108000	11.57 ± 0.03	76.52 ± 0.11	5.38 ± 0.05	6.49 ± 0.17	100.0
178.4°[h]	86400	2.81 ± 0.02	94.70 ± 0.15	1.17 ± 0.02	1.32 ± 0.11	100.0
178.4°	172800	5.43 ± 0.00	89.15 ± 0.05	2.33 ± 0.02	2.72 ± 0.06	100.0
178.4°	259200	7.85 ± 0.01	84.89 ± 0.22	3.46 ± 0.01	3.76 ± 0.23	100.0
178.4°	352800	10.31 ± 0.02	79.94 ± 0.23	4.69 ± 0.01	5.03 ± 0.20	100.0
178.4°	439200	12.25 ± 0.03	75.74 ± 0.39	5.72 ± 0.02	6.21 ± 0.45	100.0

[a] The upper set of data refers to trans-I as starting material; the lower set to cis-I. [b] Temperature control is afforded by suspending sealed ampoules in the vapors above liquids boiling under reflux. [c] Per cent of each isomer is the average of three GLC determinations and is reported ± σ, the standard deviation. [d] Total recovery is based on benzonitrile as the internal standard during the reaction. [e] Naphthalene. [f] Tetrahydronaphthalene. [g] Mixture of cis- and trans-decahydronaphthalene. [h] p-Cymene.

racemic material accordingly. Approximate values for k_5 and k_6 are obtained from plots of ln α versus time.

The refinement is effected as before by successively changing the value of each k until the deviations of experimental and calculated concentrations are minimized; then repeating the entire process to obtain the optimized values given in Table 4.

The "single" rotational processes define two thermodynamic quantities: the relative propensity of the cyano group to rotate *vis-à-vis* the vinyl group, $R_A = k_2/k_1 = k_4/k_3 = 1.48$; and the relative stability of the *trans* and *cis* diastereomers in terms of their equilibrium constant, $K = k_3/k_1 = k_4/k_2 = 2.58$. Three functions, R_A, K and k_1, for example, serve to determine the other three rate constants about the periphery of Fig. 1: $k_2 = R_Ak_1$, $k_3 = Kk_1$ and $k_4 = R_AKk_1$.

The "double" rotational processes, k_6 and k_5, relate to enantiomerization of *cis*-I and *trans*-I, respectively. They are kinetically independent of the "single" rotational processes and do not result from two-step processes such as $k_1k_4 = k_2k_3$. The expressions, $2k_6/(k_3 + k_4)$ and $2k_5/(k_1 + k_2)$, reflect the relative proportion of the "double" to "single" processes in *cis*-I and *trans*-I, respectively, 2 being the factor by which the "single" process is statistically favored. The values of these expressions, 1.62 from *cis*-I and 0.56 from *trans*-I, reveal a significant favoring of the "double" rotational process in *cis*-I.

In the framework of conventional diradical hypothesis, distribution among products is determined by the relative rates of internal rot(ation) and clos(ure). When $k_{rot} \gg k_{clos}$, a "freely" rotating diradical, having one or two of its radical centers prochiral leads to complete racemization. The extent of involvement of such an achiral, common intermediate is appropriately analyzed by the scheme in Fig. 5. A fraction, f_{nr}, of n(on)-r(andom) reaction, *not* proceeding by way of the common intermediate, is given by the expressions, $(k_2 - k_1)/(k_2 + k_1)$ and $(k_4 - k_3)/(k_4 + k_3)$, each of which reduces to $(R_A - 1)/(R_A + 1)$. The fraction of r(andomly) generated racemic product, f_r, being $(1 - f_{nr})$, it follows that $f_r = 2/(R_A + 1)$. Thus an upper limit to participation by a common, achiral intermediate in the present instance is 81%.

Another approach to fixing an upper limit to the possible involvement of an achiral common intermediate starts from the corollary that there are two products-in-common, (−)-*cis*-I and (+)-*trans*-I, which must be formed in identical ratio regardless of whether (−)-*trans*-I or (+)-*cis*-I is the starting material (see Fig. 5). Were the entire process via a common intermediate,

$$\frac{(-)\text{-}cis\text{-I}}{(+)\text{-}trans\text{-I}} = \frac{\beta k_t}{\alpha k_t} = \frac{k_1}{k_5} \text{ from } (-)\text{-}trans\text{-I and}$$

$$\frac{(-)\text{-cis-I}}{(+)\text{-}trans\text{-I}} = \frac{\beta k_c}{\alpha k_c} = \frac{k_6}{k_3} \text{ from } (+)\text{-}cis\text{-I and } \frac{k_1 k_3}{k_5 k_6} = 1.$$

To the extent that $(k_1k_3)/k_5k_6$ is not equal to 1, k_1/k_5 may be $<$ or $> k_6/k_3$. In the present example, $(k_1/k_5) < (k_6/k_3)$, β/α may have any values within the restriction $k_1/k_5 \leq \beta/\alpha \leq k_6/k_3$, and $(k_1k_3)/k_5k_6 < 1$ and may be set equal to $a = (a_5)(a_6)$, where a, a_5 and $a_6 \leqq 1$. Thus $(k_1/a_5k_5)(k_3/a_6k_6) = 1$ and the portions of k_5 and k_6 which may *not* involve a common intermediate are $(1 - a_5)k_5$ and $(1 - a_6)k_6$, respectively. There is no experimental basis for distribution of the non-random, non-racemic component between k_5 and k_6—values of a_5 and a_6 *ad libitum* are acceptable, within the restrictions above. Specifically, $1.43 < \beta/\alpha < 2.02$ and $a = a_5a_6 = 0.709$. From (−)-*trans*-I and (+)-*cis*-I, the lower limits for contribution *not* via the common intermediate are given by the expressions, respectively,

$$\frac{(k_2 - k_1) + (1 - a_5)k_5}{k_1 + k_2 + k_5} \text{ and } \frac{(k_4 - k_3) + (1 - a_6)k_6}{k_3 + k_4 + k_6}.$$

If a_6 is set equal to 0.709, at least 23.8% of the reaction of (+)-*cis*-I and 15.2% of the reaction from (−)-*trans*-I are *not* by way of a common intermediate; similarly, if a_5 is set equal to 0.709, the corresponding values are 10.8% and 21.6%, respectively.

Involvement of a common intermediate in ring expansion is limited to 83% in the case of (−)-*trans*-I and 64% in the case of (+)-*cis*-I. The remainder in (−)-*trans*-I represents a 13.2% excess of reaction by *inversion*, suprafacial and antarafacial being indistinguishable. In striking contrast, in the case of (+)-*cis*-I the not-in-common remainder represents a 35.6% excess of reaction by *retention*. Woodward–Hoffmann rules confer "allowed" status on both the **is** and **ra** processes but offer no assistance in relating a choice between them to differences in configuration of starting material.[30]

The need for elucidation of the **s**–**a** component is pressing. Until work in progress on the *trans*-propenyl analogue of I be complete, attention is recalled to the study by Berson and Dervan of optically active *trans*-1-*cis*-propenyl-2-*trans*-propenylcyclobutane (*trans*-IV) (see Fig. 2 and replace cyano by *cis*-propenyl [$H_z = CH_3$] and vinyl by *trans*-propenyl [$H_e = CH_3$]). There are two products of ring expansion: *trans*-3-methyl-4-*cis*-propenylcyclohexene (*trans*-V; 52.3% of theory) produced 95.4% in the **is** stereochemistry and 4.6% in the **ra** stereochemistry, both being Woodward–Hoffmann "allowed" processes; and *cis*-3-methyl-4-*cis*-propenylcyclohexene (*cis*-V; 7.7% of theory), 99.4% in the **rs** stereochemistry and 0.6% in the **ia**, neither of which is "allowed". Two conclusions emerge: there is no choice between **i** and **r**, their ratio being $[\mathbf{i}/\mathbf{r}]_{t\,IV} = 1.01$; there is strong preference for **s** over **a**, their ratio being $[\mathbf{s}/\mathbf{a}]_{tIV} = 36$.

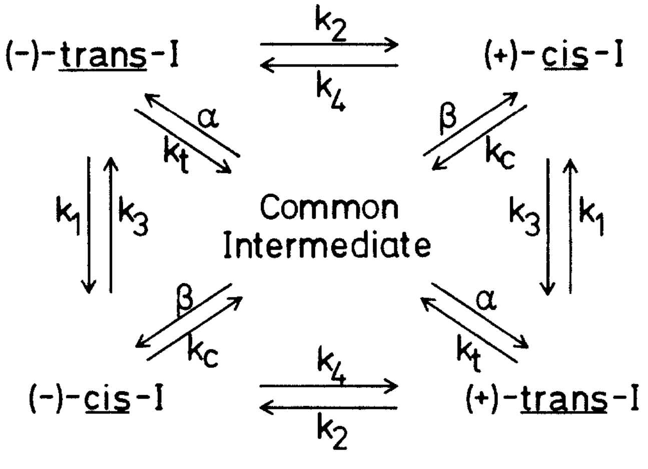


Fig. 5. A scheme for configurational reorganizations of 1-cyano-2-vinylcyclobutane (k_1, k_2, k_3, k_4 as in Fig. 1) in terms of an achiral, common intermediate, in which α and β denote the coefficients partitioning between *trans*-I and *cis*-I, respectively.

Table 7. The maximum specific rotations and absolute configurations

	$[\alpha]_D$	$[\alpha]_{578}$	$[\alpha]_{546}$	$[\alpha]_{436}$	$[\alpha]_{365}$
(1R:2R)-(-)-trans-1,2-Cyclobutanedicarboxylic Acid	$-158^{\circ\,a}$	-165.4°	-188.4°	-325.8°	-522.7°
(1R:2R)-(-)-Dimethyl-trans-1,2-cyclobutanedicarboxylate	$-148.7^{\circ\,b}$	-154.3°	-176.3°	-303.5°	-483.9°
(1R:2S)-(-)-Methyl-trans-2-vinylcyclobutanecarboxylate	$-132.2^{\circ\,c}$	-137.6°	-157.4°	-277.1°	-453.6°
(1R:2S)-(-)-trans-1-Cyano-2-vinylcyclobutane	$-175.0^{\circ\,d}$	-181.4°	-206.9°	-361.0°	-578.5°
(1S:2S)-(+)-cis-1-Cyano-2-vinylcyclobutane	$+56.9^{\circ\,d}$	$+59.0^{\circ}$	$+67.8^{\circ}$	$+122.9^{\circ}$	$+205.7^{\circ}$
(S)-(-)-Cyclohexene-4-carboxylic acid	$-108.5^{\circ\,b}$	-113.5°	-129.9°	---	-357°
(S)-(-)-4-Cyanocyclohexene	$-112.8^{\circ\,d}$	-115.9°	-132.6°	-232.1°	-374.6°

All [α] measured at 25° ± 3.0° in the following solvents: [a] H_2O, [b] CCl_4, [c] CH_3CH_2OH, [d] Cyclohexane.

Comparison of the behavior of the cyclobutanes with comparably substituted cyclopropanes is instructive. The experimental data from this work and that of Berson and Dervan are summarized in Table 5 alongside the comparable data on 1-cyano-2-isopropenylcyclopropane[4] and 1-cyano-2-*trans*-propenylcyclopropane.[7]†

It is impressive how much more effectively the cyclobutane engages in ring expansion. Thus, in neglect of cycloreversion which is not available to cyclopropane, (−)-*trans*-1 and (+)-*cis*-I, respectively, reveal 39.4% and 19.2% of the sum of automerization and ring expansion to be ring expansion, while 1-cyano-2-isopropenylcyclopropane and 1-cyano-2-*trans*-propenylcyclopropane reveal 2.5 and 3.7% and 1.5 and 3.3%, respectively. If it be granted that the rate-determining transition state for ring expansion reflect incipiently the *cis* configuration of the eventual cyclic

Table 8. Specific rotations of the products of the thermal rearrangement of (+)-*cis*-I (upper set) and (+)-*trans*-I (lower set) at 217.8°

Time (min)	Starting Material		Diastereomer Product		Cyclohexene	
	(+)-cis-I		(-)-trans-I		(-)-II	
	$[\alpha]_{578}^{a}$	$[\alpha]_{365}$	$[\alpha]_{578}$	$[\alpha]_{365}$	$[\alpha]_{578}$	$[\alpha]_{365}$
45	47.6°	163.6°	-29.6°	-93.7°	$-34.6^{\circ\,b}$	$-110.3^{\circ\,b}$
90	$44.5^{\circ\,c}$	$143.0^{\circ\,c}$	$-28.8^{\circ\,c}$	$-88.9^{\circ\,c}$	$-27.1^{\circ\,b,c}$	$-101.2^{\circ\,b,c}$
135	41.4°	142.4°	-27.5°	-86.5°	$-30.9^{\circ\,b}$	$-98.4^{\circ\,b}$
180	39.0°	133.2°	-26.6°	-84.1°	$-31.0^{\circ\,b}$	$-98.4^{\circ\,b}$
240	35.3°	121.4°	-25.2°	-79.0°	$-27.4^{\circ\,b}$	$-88.5^{\circ\,b}$
	(+)-trans-I		(-)-cis-I		(+)-II	
	$[\alpha]_{578}^{a}$	$[\alpha]_{365}$	$[\alpha]_{578}$	$[\alpha]_{365}$	$[\alpha]_{578}$	$[\alpha]_{365}$
90	164.3°	518.0°	-10.06°	-35.12°	$+17.10^{\circ\,b}$	$+55.6^{\circ\,b}$
135	$166.3^{\circ\,c}$	$521.2^{\circ\,c}$	$-10.26^{\circ\,c}$	$-34.15^{\circ\,c}$	$+16.54^{\circ\,c}$	$+55.4^{\circ\,c}$
180	160.2°	505.7°	$-9.47^{\circ\,b}$	$-32.28^{\circ\,b}$	$+16.85^{\circ}$	$+54.8^{\circ}$
240	158.6°	500.6°	-8.53°	-30.12°	$+16.52^{\circ}$	$+53.8^{\circ}$

[a] Rotations were determined at 25° ± 3°C in spectrograde cyclohexane and are reported as the average of two determinations unless noted otherwise.
[b] Rotation determined once only. [c] Rotations corrected to starting material of 100% of optical purity.

---

†Although the major results of the latter study are given in the table, we prefer to limit discussion at this time simply to a comparison with present results.

olefin, this difference may be an indication that the transformation of a cisoid conformation in starting material to a *cis* configuration in product is opposed sterically more strongly in cyclopropanes than it is in cyclobutanes. "Steric blockade" to ring enlargement by a single *cis*-propenyl[7] and to Cope rearrangement by two *cis*-propenyl groups is well established,[5,31] but has not been studied in such a manner that any difference between the 3- and 4-membered ring in response to the effect might have been elucidated.

The stereochemistry of the ring enlargement reveals a striking dependence of the ratio of inversion to retention $[\mathbf{i}/\mathbf{r}]$ on configuration of starting material. From (−)-*trans*-I, $[\mathbf{i}/\mathbf{r}]_T = 1.40$, whereas from (+)-*cis*-I, $[\mathbf{i}/\mathbf{r}]_C = 0.47$; that is, *inversion* is favored from *trans*, whereas *retention* is favored from *cis*. This phenomenon finds its parallel in the cyclopropane analogs. In Sachdev's work, for example, $[\mathbf{i}/\mathbf{r}]_T = 2.3$ and $[\mathbf{i}/\mathbf{r}]_C = 0.65$;[4] while in Barsa's work, $[\mathbf{i}/\mathbf{r}]_T = 3.1$ and $[\mathbf{i}/\mathbf{r}]_C = 0.73$.[7] Although by any reasonable estimate of error, little significance can be attached to the difference between 2.3 and 3.1, both values are doubtlessly substantially greater than one.

Since the behavior of optically active *cis*-IV has not been examined by Berson and Dervan,[5] it cannot be determined whether the contrast between *cis* and *trans* diastereomers seen here and in the analogous cyclopropanes extends to their system. This situation is the more regrettable, given the care and thoroughness with which the behavior of the *trans* diastereomer was pursued. Nonetheless, informative, if fragmentary, conclusions may be drawn from their studies of racemic *cis*-IV.

On one side, were theoretical prejudice to lie in the direction of making *cis*-IV as similar to *trans*-IV as possible, it would be desirable to make the ratio in ring expansion of **a**/**s** as small as possible. (Recall that in the reactions of *trans*-IV to *cis*-V and *trans*-V, $[\mathbf{a}/\mathbf{s}]_{TIV \to CV} = 0.006$ and $[\mathbf{a}/\mathbf{s}]_{TIV \to TV} = 0.049$). This would be done by ascribing the entire generation of *cis*-V to the **is** process and of *trans*-V to the **rs** process, with the consequence that the ratio, $[\mathbf{i}/\mathbf{r}]_{CIV} = 0.186$, which is much smaller than is found for *trans*-IV ($[\mathbf{i}/\mathbf{r}]_{TIV} = 1.006$) or even the cyclopropanes noted in Table 5.

On the other side, if theoretical speculation were to run in the direction of making $[\mathbf{i}/\mathbf{r}]_{CIV} \geqq 1.00$ so that the behaviour of *cis*-IV would be more in line with that of *trans*-IV, the production of *cis*-V would be ascribed entirely to the **is** process ($k_{C\mathbf{is}} = 5.4 \times 10^{-6}\,\mathrm{sec}^{-1}$), while portions of $k_{C\mathbf{ia}} \geqq 11.8 \times 10^{-6}\,\mathrm{sec}^{-1}$ and $k_{C\mathbf{rs}} \leqq 17.2 \times 10^{-6}\,\mathrm{sec}^{-1}$ would need to be assigned to the production of *trans*-V. The inevitable consequence would be the raising of the ratio, $[\mathbf{a}/\mathbf{s}]_{CV \to TV}$, to a value, 0.686, which is far higher than either value from *trans*-IV noted above. It might thus be possible to predict that optically active *cis*-IV would be found to depart strikingly from the pattern shown by the *trans*-diastereomer.

The conclusion the authors[5] draw from their experience with *trans*-IV is repeated here: "For the present, a simpler and hence preferable interpretation would describe the major reactions, **si** and **sr** as concerted processes, **si** allowed,[30] but only slightly over **sr**, which is forbidden."[32] Analogously, an interpretation would describe the *minor* reaction (*cis*-IV → *cis*-V) as an undetermined admixture of concerted, allowed processes, **is** and **ra**, and the *major* reaction as a combination of concerted, forbidden processes, **ia** and **rs**. Such efforts to analyze the stereochemistry of not obviously concerted thermal reorganizations in terms of conservation of orbital symmetry and control by subjacent orbitals constitute a valid part of current diagnostic procedure, however futile they may seem when they fail to provide insight of explicative or predictive value.

The theoretical conceptual scheme of a continuum between strongly concerted reactions, operational criteria for the recognition of which exist, and not concerted reactions, operational criteria for the positive identification of which may be inaccessible, leaves an area of *not obviously concerted* reactions, some or all of which may in reality be non-concerted. In these instances, alternate hypotheses need to be explored. Such appears to be the case here, where efforts to understand each member of the set of constitutional changes in terms of a concerted model succeeds with the Diels–Alder-like change, but fails with the cycloaddition/reversions, automerizations and ring expansions.

Key factors in the configurational and constitutional aspects of the not obviously concerted automerizations and ring enlargements are self-evidently (1) intramolecular bond-breaking, (2) internal rotation and (3) reforming of bonds. While the hypothesis of a common intermediary diradical serves as a good basis for predicting the enthalpies of activation, it is not of much help in the interpretation and prediction of internal rotations.

We continue to explore the R_A factor as a help in rationalizing and predicting the stereochemical consequences of internal rotations. The small size of the preference when expressed as $\Delta\Delta G^{\neq}$ or $\Delta\Delta H^{\neq}$ and $\Delta\Delta S^{\neq}$ should serve as a warning against expecting dramatic success. Nonetheless, were the R_A factor of 1,48, which reflects a small preference of the cyano group to rotate in the automerization of *cis*-I and *trans*-I, to be reflected in the ring expansion, it could lead to the preferential rotation of the cyano group, and in such a sense as to turn the cyano group away from the center of the ring. In the *trans* diastereomer, such a motion would present the **i** face of the cyano carbon radical to the **s** face of the relatively passive, cisoid allylic radical, while, in the instance of the *cis* diastereomer, the **r** face would be presented (Fig. 6).

Although an application of the R_A factor to ring expansion is consistent with the reversal of the ratio of inversion to retention seen in shifting from *trans*-I ($[\mathbf{i}/\mathbf{r}]_T = 1.40$) to *cis*-I ($[\mathbf{i}/\mathbf{r}]_C = 0.47$), it is offered less as an explanation of the major result then as an illustration of an alternate way of thinking about preferences among rotational possibilities. At the moment, it does not seem fruitful to wonder about the role of double rotational processes or about the effect worked on R_A by the non-equilibrium cisoid conformation required of the vinyl group participating in ring expansion.

In this work, a close similarity between four- and three-membered rings in automerization and ring expansion has been established. Because criteria of concertedness are not satisfied, these reactions are classified as not obviously concerted thermal reorganizations. Consistently, their properties do not respond well to analysis by theories of concerted

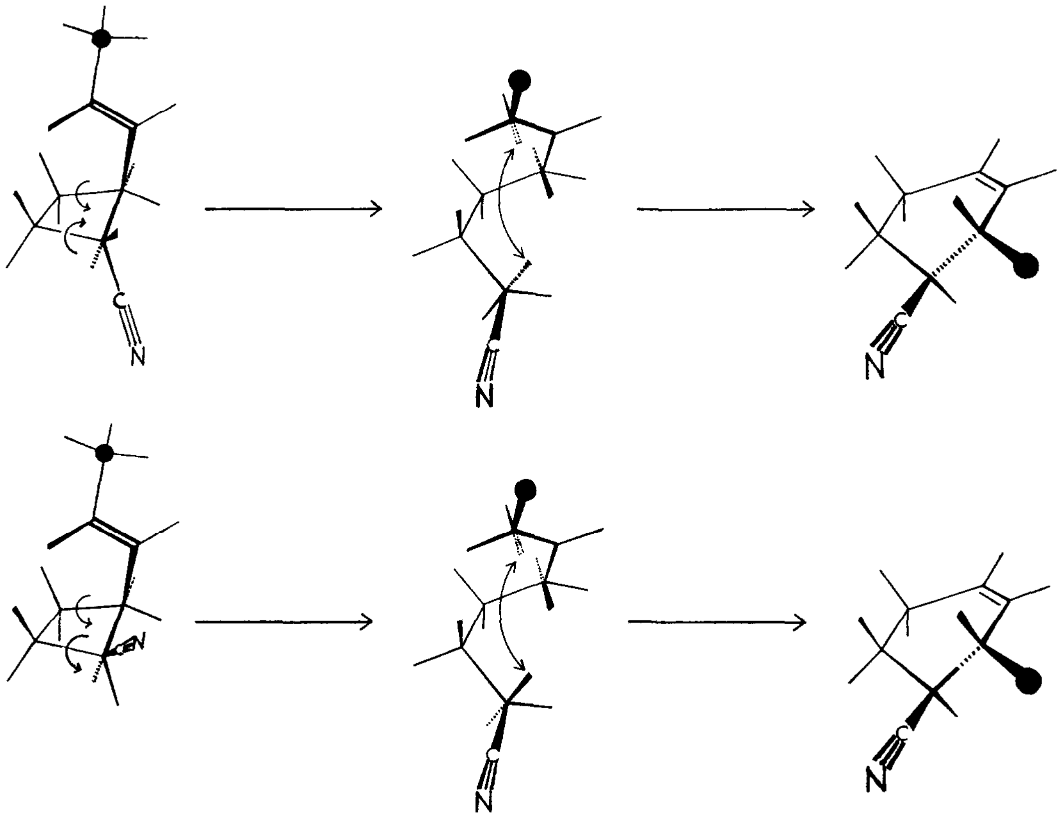


Fig. 6. Conformational depiction of the constitutional reorganization of (1R:2S)-(−)-*trans*-I (upper) and (1S:2S)-(+)-*cis*-I (lower) in their configurationally favored mode to (S)-(−)-4-cyanocyclohexene (II).

processes, but appear to call for a more useful understanding of internal rotations and their role in transition states.

EXPERIMENTAL

General. Optical rotations are determined on a Perkin–Elmer 141 digital readout polarimeter and are reported as specific rotations, the concentration being expressed in grams per 100 ml of the designated solvent. Observed rotations may be found in dissertation.[1] Volumetric errors are estimated to be ±1.0% "Ethanol" is abs EtOH, CCl_4 and cyclohexane are spectrograde.

Spectroscopic information is obtained in the following ways:

NMR: Varian T-60 spectrometer reported in ppm downfield from TMS (δ); IR: Perkin–Elmer 337 grating spectrophotometer; mass spectra: AEI Model MS-9 double focussing mass spectrometer. M and bps are uncorrected. Microanalyses are by Scandinavian Microanalytical Laboratory, Herlev, Denmark.

Perkin–Elmer 990 gas chromatograph with a flame ionization detector and Autolab 6300 digital integrator is used for quantitative analyses. Purification and separation of larger quantities is accomplished on Aerograph A90-P and A90-P3 gas chromatographs.

The following columns are used frequently in the sequel. A: 6′ × 0.25″ o.d., 20% Carbowax 20M on 60/80 mesh non-acid-washed Chromosorb P; B: 5 m × 0.25″, 20% General Electric methyl silicone gum rubber (SE-30) on 60/80 mesh Chromosorb P washed with NaOH in methanol; C: 5 m × 0.25″, 20% 1,2,3-tris-(2-cyanoethoxy)-propane (TCEP) on 60/80 mesh non-acid-washed Chromosrb P; D: 3 m × 0.25″, 20% Carbowax 20 M on 50/60 mesh Anakrom-acid, base-washed and silanized (ABS); E: 300′ × 0.01″, Carbowax 20 M capillary.

Racemic trans- *and* cis-1-*cyano*-2-*vinylcyclobutane* (I). These materials were prepared following the general procedure of Dilling.[9] Into a 420 ml photolysis flask with immersion-well and two side-arms, one fitted with a calcium sulfate drying tube and the other with a gas inlet tube, were placed 171 ml (2.6 mol) freshly distilled acrylonitrile and 44.4 ml (0.26 mol) 2,3-butanedione. The flask was placed into a one-gallon Dewar flask containing dry-ice and acetone; the lamp housing was cooled with MeOH circulating through a dry-ice-acetone bath; butadiene-1,3 (Matheson Instrument Grade) (226 ml, 2.6 mol) was then distilled into the cooled flask and the mixture was irradiated with light from a 450-w, high-pressure Hanovia lamp filtered through Pyrex. The progress of the photolysis was followed by glpc (A: 125°, He 60 ml/min). After irradiation for two 8 hr periods, excess butadiene was allowed to evaporate at rt and excess acrylonitrile and butanedione were removed by evaporation at rt and 10 mm. The distilled residue (b.p. 42°/2 mm) was separated into its components by preparative glpc (A: 125°, He 60 ml/min):

trans-I: ret. time 8.5 min; 880 mg; NMR (CCl_4) 2.2 (m, 4 H), 2.8 (m, 1 H), 3.2 (m, 1 H), 5.0 and 5.2 (m, 2 H), 5.9 (m, 1 H); IR (CCl_4) 2240 ($C{\equiv}N$), 3100 cm^{-1} (=CH).

cis-I: ret. time 12 min; 800 mg; NMR (CCl_4) 2.3 (m, 4 H), 3.3 (m, 2 H), 5.0, 5.1 and 5.3 (m, 2 H), 6.0 (m, 1 H); IR (CCl_4) 2235 ($C{\equiv}N$), 3075 cm^{-1} (=CH).

4-Cyanocyclohexene (II): ret. time 15.5 min; 400 mg; NMR (CCl_4) 2.2 (m, 5 H), 2.8 (m, 2 H), 5.7 (d, 2 H); IR (CCl_4) 2240 cm^{-1} ($C{\equiv}N$).

The NMR spectra agree with those reported.[9]

Methyl trans- *and* cis-2-*vinylcyclobutane*-1-*carboxylate.* These compounds were prepared by the same general procedure used for the preparation of the corresponding nitriles. Freshly distilled methyl acrylate (194 ml, 2.26 mol), 2,3-butanedione (19.2 ml, 0.226 mol), and 2.26 mol of butadiene were irradiated for 40 hr in 10 hr periods. The progress of the photolysis was followed by analysis of aliquots by glpc (B: 140°, He 60 ml/min). After excess butadiene, methyl acrylate, and butanedione had been removed, a small amount of the distilled (b.p. 32°/0.8 mm) residue was separated by preparative glpc under the same conditions used for analysis:

Methyl *trans*-2-vinylcyclobutane-1-carboxylate: ret. time 26 min; NMR (CCl_4) 2.0 (m, 4 H), 3.0 (m, 2 H), 3.6 (s, 3 H), 5.1, 5.2, 4.9 (m, 2 H), 5.9 (m, 1 H); IR (CCl_4) 1740 cm^{-1} (C=O); mass spectrum *m/e*: calc. for $C_8H_{12}O_2$: 140.0837, found: 140.0844.

Methyl *cis*-2-vinylcyclobutane-1-carboxylate: ret. time 28 min; NMR (CCl_4) 2.1 (m, 4 H), 3.2 (m, 2 H), 3.6 (s, 3 H), 4.9 and 5.1 (m, 2 H), 5.9 (m, 1 H); IR (CCl_4) 1740 cm^{-1} (C=O); *m/e*: calc. for $C_8H_{12}O_2$: 140.0837, found: 140.0840.

Methyl cyclohexene-4-carboxylate: ret. time 45 min; NMR (CCl_4) 2.2 (m, 7 H), 3.7 (s, 3 H), 5.7 (s, 2 H); IR (CCl_4) 1740 cm^{-1}.

Methyl trans-2-*vinylcyclobutane*-1-*carboxylate.* An alternate preparation proceeded from *trans*-cyclobutane-1,2-carboxylic acid (Aldrich Chemical Co.) by way of the dimethyl ester and the monomethyl ester according to Schroff, Stewart, Uhm and Wheeler.[26] Reduction to methyl *trans*-2-hydroxymethylcyclobutane-1-carboxylate also followed their procedure but modified according to Brown and Subba Rao.[33]

Oxidation to *trans*-2-carbomethoxycyclobutanecarboxaldehyde was effected by dimethyl sulfoxide according to Parikh and Doering.[27] Into a flame-dried, 1-l three-necked flask which was attached to a 250-ml flask by a 90°-bend, glass connector and was fitted with N_2 inlet, drying tube, and magnetic stirrer were placed 166 ml of dry Et_3N, 23.8 g (0.165 mol) of methyl *trans*-2-hydroxymethylcyclobutane-1-carboxylate and 166 ml of dry DMSO. After addition of a slurry of $Et_3N{-}SO_3$ (69.5 g, 0.495 mol) in 50 ml of DMSO, the mixture was stirred overnight, acidified with 3 N HCl and extracted with CH_2Cl_2. The extracts were washed with H_2O, sat $NaHCO_3$ aq and dried ($MgSO_4$). Distillation afforded 10.97 g (47 %) of the aldehyde ester: b.p. 63°/3 mm; IR (CCl_4) 1745 cm^{-1} (ester C=O), 1735 (shoulder, aldehyde C=O); NMR (CCl_4) 2.2 (m, 4 H), 3.35 (m, 2 H), 3.75 (s, 3 H), 10.0 (s, 1 H); 2,4-dinitrophenylhydrazone, m.p. 139°. (Found: C, 48.3; H, 4.5, N, 17.5 %.) Calc. for $C_{13}H_{14}N_4O_6$: C, 48.5; H, 4.4; N, 17.4 %).

Conversion to methyl *trans*-2-vinylcyclobutane-1-carboxylate followed the procedure of Greenwald, Chaykovsky and Corey.[28] Better yields were obtained using an excess of Wittig reagent: NaH (1.83 g of a 57 % mineral oil dispersion; 0.039 mol) and methyl triphenylphosphonium bromide (14.28 g, 0.040 mol) in 40 ml DMSO. After 15 min of stirring at rt, 2.90 g (0.026 mol) *trans*-2-carbomethoxycyclobutane-1-carboxyaldehyde was added and stirring was continued at rt overnight. Isolation followed the published procedure: yield 2.39 g (62.5 %). Analysis by glpc (C: 110°, He 60 ml/min) revealed a 9:1 mixture of methyl *trans*-2-vinylcyclobutane-1-carboxylate (ret. time 29.5 min) and the *cis* isomer (ret. time 33 min), identical to previously synthesized samples.

Resolution of trans-2-*vinylcyclobutane*-1-*carboxylic acid.* Saponification of the crude (9:1) *trans* ester (reflux for 12 hr in 80 ml 80 % eq. MeOH containing 8 g (0.14 mol) KOH) afforded 9.5 g (78 %) of crude acid, which could be purified by distillation: b.p. 55°/0.05 mm; NMR (CCl_4) 2.1 (m, 4 H), 3.1 (m, 2 H), 5.1 (m, 2 H), 6.0 (m, 1 H), 12.5 (s, 1 H); IR (CCl_4) 1700 cm^{-1} (C=O); mass spectrum *m/e*: Calc. for $C_7H_{10}O_2$: 126.0681, found: 126.0688.

The crude acid (14.5 g, 0.115 mol) and quinine (37.26 g, 0.115 mol) were dissolved in 50 ml abs EtOH, treated with 400 ml water and heated to boiling, enough abs EtOH having been added to redissolve all solid material. Colorless needles deposited on standing at rt overnight. Since the crude *trans*-acid contained 5–10 % of the *cis*-acid, the progress of the resolution was followed by recovering samples of acid from the salt, esterifying with ethereal diazomethane, separating pure *trans* ester by glpc (C: 120°, He 60 ml/min) and measuring its rotation.

After one recrystallization of the salt, methyl *trans*-2-vinylcyclobutane-1-carboxylate had $[\alpha]^{27}_{578}$ + 59.9°, $[\alpha]^{27}_{365}$ + 196.4° (*c* 1.6033, EtOH); after second recrystallization: $[\alpha]^{25}_{578}$ + 107.8°, $[\alpha]^{25}_{365}$ + 352.5 (*c* 1.1337, EtOH); after third recrystallization (16.73 g of salt): $[\alpha]^{25}_{578}$ + 127.5°, $[\alpha]^{25}_{365}$ + 417.0° (*c* 0.7386, EtOH); after three further recrystallizations: $[\alpha]^{27}_{578}$ + 135.2°, $[\alpha]^{27}_{365}$ + 441.8 (*c* 0.9134, EtOH). One more recrystallization of the salt gave methyl ester $[\alpha]^{27}_{578}$ + 132.3°, $[\alpha]^{27}_{365}$ + 434.6 (*c* 0.2901, EtOH). After the 6th and 7th recrystallization of the salt, the resulting *trans* methyl ester was free of *cis* isomer.

From the mother liquor of the first recrystallization, methyl ester was obtained consisting of 10 % *cis* isomer and 90 % *trans* ester, $[\alpha]^{27}_{578}$ − 118.7°, $[\alpha]^{27}_{365}$ − 387.4 (*c* 0.9510, EtOH).

(−)-trans-1-*Cyano*-2-*vinylclobutane* [(−)-trans-I]. Conversion of 4.26 g (0.034 mol) of (+)-*trans*-carboxylic acid [corresponding methyl ester: $[\alpha]^{27}_{578}$ + 137.5°, $[\alpha]^{27}_{365}$ + 417.0° (*c* 0.7386, EtOH)] by the procedure of Doering and Sachdev[2] afforded 2.93 g (75 %) of colorless (+)-*trans*-2-vinylcyclobutane-1-carboxamide: m.p. 85° after recrystallization from CH_2Cl_2–pet. ether; NMR ($CDCl_3$) 2.2 (m, 4 H), 3.2 (m, 2 H), 5.0 (m, 1 H), 5.3 (m, 1 H), 6.2 (m, 1 H); IR ($CDCl_3$) 3530 cm^{-1} (NH), 3400 (N–H), 1675 (C=O); $[\alpha]_{578}$ + 107.5°, $[\alpha]_{365}$ + 393.9° (*c* 2.706, $CHCl_3$). A racemic sample, m.p. 102–103°, had a mass spectrometric mol wt: *m/e*: Calcd. for $C_7H_{11}NO$: 125.08406, Found: 125.08404.

Following the procedure of Doering and Sachdev,[4] 1.44 g (11.5 mol) of (−)-carboxamide [from (−)-*trans* methyl ester: $[\alpha]^{27}_{578}$ − 118.7°, $[\alpha]^{27}_{365}$ − 387.4° (*c* 0.9510, EtOH)] was converted to crude nitrile, which was separated into two components by preparative glpc (D: 120°, He 60 ml/min): (−)-*trans*-1-cyano-2-vinylcyclobutane [(−)-*trans*-I]: ret. time 16 min; 592 mg; $[\alpha]^{27}_{578}$ − 157.0°, $[\alpha]^{27}_{365}$ − 497.0° (*c* 0.3235, cyclohexane); NMR and IR identical to those of a sample prepared above; (−)-*cis*-1-cyano-2-vinylcyclobutane [(−)-*cis*-I]: ret. time 24 min; 68 mg; $[\alpha]^{27}_{578}$ − 9.3°, $[\alpha]^{27}_{365}$ − 30.8° (*c* 1.0578, cyclohexane; NMR and IR identical to those of sample prepared above).

That the glpc procedure caused no racemization was determined in separate experiments with (+)-*trans*-I, $[\alpha]^{25}_{578}$ + 156.2°, $[\alpha]^{25}_{365}$ + 493.0 (*c* 1.2681, cyclohexane), before glpc and $[\alpha]^{25}_{578}$ + 155.8°, $[\alpha]^{25}_{365}$ + 490.9° (*c* 0.9825, cyclohexane) after glpc; and with (+)-*cis*-I, $[\alpha]^{25}_{578}$ + 50.8°, $[\alpha]^{25}_{365}$ + 174.7° (*c* 0.7480, cyclohexane) after glpc.

Epimerization of trans- *and* cis-*I*. Following the procedure of Doering and Sachdev,[2] 22 mg *trans*-I in 0.2 ml of dry DMSO at 30° was treated with 10 mg t-BuOK for 10 min. Quenching with 1 ml water and extraction with pentane followed by glpc (E: 130°, He 35 psi) revealed *trans*-I (76.31 %) and *cis*-I (23.68 %); K = 0.310. Repetition of the experiment with *cis*-I gave *trans*-I (75.64 %) and *cis*-I (24.36 %); K = 0.322.

In a separate experiment with *trans*-I, *cis*-I was recovered by glpc (D: 120°, He 60 ml/min): NMR (CCl_4) 2.3 (m, 4 H), 3.3 (m, 2 H), 5.0, 5.2, 5.4 (m, 2 H), 6.0 (m, 1 H); IR (CCl_4) 2240 cm^{-1} ($C{\equiv}N$).

(+)-*cis*-1-Cyano-2-vinylcyclobutane [(+)-*cis*-I]. An 881-mg sample of (−)-*trans*-I ($[\alpha]^{27}_{578}$ − 157.0°, $[\alpha]^{27}_{365}$ − 497.0° (*c* 0.3235, cyclohexane)) was epimerized by the procedure above. Separation by preparative glpc (D: 120°, He 60 ml/min) afforded (+)-*cis*-I, $[\alpha]^{22}_{578}$ + 51.0°, $[\alpha]^{22}_{365}$ + 175.2° (*c* 1.0623, cyclohexane) after being rechromatographed once, and recovered (−)-*trans*-I, $[\alpha]^{22}_{578}$ − 156.6°, $[\alpha]^{22}_{365}$ − 493.7 (*c* 0.7318, cyclohexane).

(S)-(−)-4-*Cyanocyclohexene.* Following the procedure used above for 1-cyano-2-vinylcyclobutane, a 1.26-g (10 mmol) sample of (S)-(−)-4-cyclohexene-1-carboxylic acid ($[\alpha]^{25}_{578}$ − 88.99°, $[\alpha]^{25}_{365}$ − 279.6° (*c* 0.7192, CCl_4), 78.4% optically pure) was treated with 1.01 g (10 mmol) Et_3N and 1.35 ml ethyl chloroformate followed by ammonia. The resulting amide (239 mg, 1.9 mmol) on treatment with 363 mg (1.9 mmol) of *p*-toluenesulfonyl chloride then afforded nitrile, $[\alpha]^{25}_{578}$ − 90.9°, $[\alpha]^{25}_{365}$ − 293.2° (*c* 0.8117, cyclohexane). The rotation of optically pure 4-cyanocyclohexene (obtained by correction for the 78.4% optical purity of starting acid) is $[\alpha]^{25}_{578}$ − 115.9°, $[\alpha]^{25}_{365}$ − 374.6°.

Dimethyl (1R:2R)-(−)-trans-*cyclobutane*-1,2-*dicarboxylate*. Treatment of 0.0432 g (0.3 mmol) of (1*R*:2*R*)-(−)-cyclobutane-1,2-dicarboxylic acid ($[\alpha]^{25}_{D}$ − 155.0°, $[\alpha]^{25}_{578}$ − 162.1°, $[\alpha]^{25}_{365}$ − 512.4° (*c* 1.1847, H_2O), 98.10% optically pure) with ethereal diazomethane, followed by washing with sat $NaHCO_3$ and water led to 0.04128 g (80%) of the dimethyl ester: $[\alpha]^{25}_{D}$ − 146.0°, $[\alpha]^{25}_{578}$ − 151.4°, $[\alpha]^{25}_{365}$ − 474.9° (*c* 0.7200, CCl_4). The maximum rotation of the diester at only one wavelength has been reported[5] ($[\alpha]^{25}_{D}$147°) and agrees with our value of $[\alpha]^{25}_{D}$ − 148.7°, $[\alpha]^{25}_{578}$ − 154.3°, $[\alpha]^{25}_{365}$ − 483.9°.

Conversion of methyl (1R:2S)-(−)-trans-2-*vinylcyclobutane*-1-*carboxylate to dimethyl* (1R:2R)-(−)-trans-*cyclobutane*-1,2-*dicarboxylate*. To 0.07784 g of vinyl ester (0.556 mol) ($[\alpha]^{25}_{D}$ − 114.0°, $[\alpha]^{25}_{578}$ − 118.7°, $[\alpha]^{25}_{365}$ − 391.3° (*c* 0.3065), EtOH) in 20 ml of 80% aqueous t-BuOH kept at pH 8 by the addition of solid K_2CO_3, 0.984 g (4.60 mmol) of sodium metaperiodate and 10 mg $KMnO_4$ in 27.8 ml water was added with stirring.[34] After the mixture had been stirred for 10 min, removal of t-BuOH under reduced pressure gave a residue which was dissolved in 10 ml water and acidified with 10% HCl. The dried ($MgSO_4$) ether extract thereof was esterified (diazomethane). Preparative glpc (D: 150°, He 100 ml/min) of the crude ester gave 0.05114 g (53.5%) of dimethyl cyclobutane-1,2-dicarboxylate ($[\alpha]^{25}_{D}$ − 128.3°, $[\alpha]^{25}_{578}$ − 133.1°, $[\alpha]^{25}_{365}$ − 417.9° (*c* 0.5545, CCl_4), 86.3% optically pure). Based on the maximum rotation of the diester, the maximum rotation of vinyl carboxylate is $[\alpha]^{25}_{D}$ − 132.2°, $[\alpha]^{25}_{578}$ − 137.6°, $[\alpha]^{25}_{365}$ − 453.6°.

General procedure for thermal rearrangements. Thermal rearrangements were performed in Pyrex ampoules which had been soaked in NH_4OH overnight, rinsed with distilled water until the washings were neutral, then rinsed with acetone and dried. Immediately before use, the ampoules were flame-dried with nitrogen-purging. Two sizes were used: A: 15 cm × 1 cm 0.d. with 10 cm × 0.6 cm 0.d. stem (~8 ml volume when sealed) and B: 20.5 cm × 1.2 cm 0.d. with 11 cm × 0.7 cm 0.d. stem (~16 ml volume when sealed). Samples of nitrile were introduced via microsyringe; ampoules were sealed under 10^{-4} mm pressure and suspended in the vapors of a boiling solvent bath by a Cu wire fastened to a hook at the end of the ampoule. The temp of the vapors was measured with an iron-constantan thermocouple and a Leeds and Northrup No. 8686 millivolt potentiometer.

Kinetics of the thermal rearrangement of racemic trans-*I and* cis-*I*. The rates of reaction of *trans*-I and *cis*-I were determined at the bps of four solvents: naphthalene (217.8°), tetrahydronaphthalene (207.1°), a constant boiling mixture of *cis*- and *trans*-decalin (191.7°), and *p*-cymene (178.4°). An equal volume of purified benzonitrile was admixed to serve as internal standard. About 12 μl of the nitrile–benzonitrile mixture was introduced into each of six ampoules, size A. Five of the ampoules were suspended at once in the vapor bath, to be removed one each at the end of specified intervals. Prior to analysis, ampoules were opened by cooling their stems in liquid N_2 just before being broken off and given an injection of 100 μl of *m*-xylene. Products were analyzed by glpc (E: 130°, He 35 psi) on the Perkin–Elmer 990. Relative areas were determined with the aid of an Autolab 6300 digital integrator. Response factors for *cis*-I, *trans*-I, 4-cyanocyclohexene and acrylonitrile were determined relative to benzonitrile (ret. time 47.5 min, response factor: 1.000): *cis*-I (25.5 min), 0.957; *trans*-I (34.0 min), 0.928; II (41.5 min), 0.949; and III (10.2 min), 0.722. The data are summarized in Table 6.

Rate constants for the conversion of *cis*-I and *trans*-I to individual products were extracted on the basis of the simultaneous differential equations derived from the kinetic scheme of Fig. 3. Solution of the equations was effected by numerical integration using trial values of k_1 through k_6, comparing the calculated concentrations with the experimental ones, and varying the rate constants systematically until the best agreement of calculated and experimental concentrations was obtained. A computer program for numerical integration by the method of Runge–Kutta, written by Prof. M. Saunders, Yale University, for the PDP-10, was modified by Mr. David Dixon for use on the PDP 11/45, to include an iterative variation of rate constants and the computation of error described below.

For each of *trans*-I, *cis*-I, II and III, agreement of the experimental and observed concentrations (c_i) over time is expressed as

$$\bar{\sigma}_{c_i} = \left(\sum_{1}^{n} [c_i(\text{calc}) - c_i(\text{exp})]^2/n - 1\right)^{1/2}$$

where c_i is the concentration of the *i*th component and n is the number of experimental points. A specified rate constant is then varied by a given fraction (e.g. $k_{t,c}$ becomes $k_{t,c} + 0.1\,k_{t,c}$) and the calculation is re-performed. The procedure is repeated for the number of iterations requested.

In general, a set of trial rate constants is taken and each one is varied successively while the others are kept constant. The four sets of values of $\bar{\sigma}_i$ were each plotted vs the various values of k_i. In the event, each of the six rate constants is strongly coupled to two $\bar{\sigma}_i$ and very weakly coupled to the remaining two $\bar{\sigma}_i$. Thus, for example, $\bar{\sigma}_t$ and $\bar{\sigma}_c$ are sensitive, while $\bar{\sigma}_{II}$ and $\bar{\sigma}_{III}$ are insensitive, to variation in $k_{t,c}$. The values of k_i at minima in the most sensitive $\bar{\sigma}_i$ are then reinserted into the minimization procedure until each better new k_i effects less than a 1% improvement in the next iteration. At this point the minimum in $\bar{\sigma}_t$ and $\bar{\sigma}_c$, for example, appears at the same value of k. In Table 2 optimized rate constants at each temperature are reported with an uncertainty represented by the range of rate constant sufficient to increase $\bar{\sigma}_i$ to twice the value of ($\bar{\sigma}_i$) minimum. In the Ph.D. dissertation the results of all twenty-four correlations may be found.[1]

Thermal rearrangement of (+)-cis-I *and* (+)-trans-I. Rearrangements were carried out by the general procedure described above. (+)-*Cis*-I ($[\alpha]^{23}_{578}$ + 50.90°, $[\alpha]^{23}_{365}$ + 175.2° (*c* 0.8643, cyclohexane) was indicated to be 85.2% of optical purity on the basis of the indicated maximum rotation, all of which are collected in Table 7. For each point several ampoules of size B were filled with 50 μl (~700 mm final pressure) of (+)-*cis*-I and heated at 217.8° ± 0.3°. The contents of the ampoules were separated by glpc (D: 120°, He 60 ml/min) into pure components, which were rechromatographed and used for two determinations of specific rotation if enough material was available. The samples used for these determinations were checked for contamination by glpc on a second column: E at 130° and He, 35 psi. Five points at 45, 90, 135, 180, and 240 min were taken.

For the 90-min point, the starting material was 79.5% of optical purity and specific rotations for this point were corrected to 100% optical purity.

The sample of (+)-*trans*-I used as starting material for 90, 180 and 240 min had $[\alpha]^{25}_{578}$ + 167.7°, $[\alpha]^{25}_{365}$ + 529.9° (*c* 0.6805, cyclohexane) and was 91.6% optically pure. The sample of (+)-*trans*-I used for the 135 min point had $[\alpha]^{25}_{578}$ + 163.4°, $[\alpha]^{25}_{365}$ + 516.8° (*c* 0.6016, cyclohexane), 99.3% optically pure. The corrected results are summarized in Table 8. Rate constants were obtained in the same manner as for racemic material on the basis of the differential equations representing the kinetic schemes in Figs. 1 and 2. The refined rate constants with corresponding uncertainties as previously defined are collected in Table 4.

Thermal rearrangement of (−)-II. Twelve μl of (−)-II ($[\alpha]^{25}_{578}$ − 90.9°, $[\alpha]^{25}_{365}$ − 293.3° (*c* 0.9061, cyclohexane)) was heated for 12 hr at 217.8° ± 0.3°. The recovered II (D: 120°, He 60 ml/min) showed $[\alpha]^{25}_{578}$ − 88.8°, $[\alpha]^{25}_{365}$ − 286.8° (*c* 0.4180, cyclohexane). No other products were formed.

Thermal rearrangement of trans-*I and* cis-*I in lead-potash tubes.* Two-μl samples of *cis*-I and *trans*-I were heated in tubes of Corning 0120 glass (6.1 mm o.d. × 4 in) for four hours at 217.8° ±0.3°. Analysis (E: 135°, He 35 psi): *trans*-1: 81.2% *trans*-I. 5.9% *cis*-I, 6.6% II, and 6.2% III; *cis*-I: 64.6% *cis*-I, 14.9% *trans*-I, 12.9% III, 8.0% II.

Thermal rearrangement of (+)-cis-*I at* 1 mm *pressure.* Into a 12-L Pyrex flask in an air-thermostat heated to 217° 40 mg of (+)-*cis*-I ($[\alpha]^{25}_{578}$ + 41.6°, $[\alpha]^{25}_{365}$ + 143.0 (*c* 1.0505, cyclohexane), 69.5% optically pure) was transferred by vacuum within 5 min. After 240 min, the product was withdrawn quantitatively by vacuum transfer into a received cooled in liquid N_2. Analysis: (+)-*cis*-I (69.0%), $[\alpha]^{25}_{578}$ + 28.4°, $[\alpha]^{25}_{365}$ + 97.3 (*c* 0.9992, cyclohexane); (−)-*trans*-I (16.3%), $[\alpha]^{25}_{578}$ − 20.2°, $[\alpha]^{25}_{365}$ − 63.1 (*c* 0.4944, cyclohexane); (−)-II (8.3%), $[\alpha]^{25}_{578}$ − 22.6°, $[\alpha]^{25}_{365}$ − 73.1 (*c* 0.2216 cyclohexane); III (6.31%).

Thermal rearrangement of (+)-trans-I *and* (+)-cis-*I in acetonitrile.* A 50 mg sample of (+)-*cis*-I ($[\alpha]^{25}_{578}$ + 41.6°, $[\alpha]^{25}_{365}$ + 143.0° (*c* 1.0505, cyclohexane), 69.4% optically pure) in 0.5,ml CH_3CN was heated for 240 min at 217.8° ± 0.3° in a Pyrex tube. Analysis: *cis*-I (60.7%), $[\alpha]^{25}_{578}$ + 33.8°, $[\alpha]^{25}_{365}$ + 116.0 (*c* 0.9752, cyclohexane); *trans*-I (10.1%), $[\alpha]^{25}_{578}$ − 14.5°, $[\alpha]^{25}_{365}$ − 44.2 (*c* 0.1855, cyclohexane); II (12.7%), $[\alpha]^{25}_{578}$ − 12.7°, $[\alpha]^{25}_{365}$ − 40.2° (*c* 0.4646, cyclohexane); and III (16.43%).

A 200-mg sample of (+)-*trans*-I ($[\alpha]^{25}_{578}$ + 160.2°, $[\alpha]^{25}_{365}$ + 505.6° (*c* 0.6504, cyclohexane), 87.4% optically pure) in 2.0 ml CH_3CN was treated as above. Analysis: *trans*-I (78.18%), $[\alpha]^{25}_{578}$ + 153.8°, $[\alpha]^{25}_{365}$ + 485.0 (*c* 0.7905, cyclohexane); *cis*-I (5.24%), $[\alpha]^{25}_{578}$ − 5.5°, $[\alpha]^{25}_{365}$ − 19.8° (*c* 0.7186, cyclohexane); II (10.0%), $[\alpha]^{25}_{365}$ + 7.53 (*c* 0.6737, cyclohexane); and III (6.55%).

Thermal rearrangement of (+)-trans-I *in benzene.* A 200-mg sample of (+)-*trans*-I ($[\alpha]^{25}_{578}$ + 164.3°, $[\alpha]^{25}_{365}$ + 518.2 (*c* 0.7116, cyclohexane), 89.6% optically pure) in 2.0 ml benzene was heated for 4 hr at 217.8° ± 0.3° in a Pyrex tube. Analysis: *trans*-I (77.5%), $[\alpha]^{25}_{578}$ + 150.3°, $[\alpha]^{25}_{365}$ + 475.9° (*c* 0.6230, cyclohexane); *cis*-I (5.4%), $[\alpha]^{25}_{578}$ − 5.1°, $[\alpha]^{25}_{365}$ − 18.1° (*c* 0.3276, cyclohexane); II (10.9%), $[\alpha]^{25}_{578}$ + 7.66°; $[\alpha]^{25}_{365}$ + 24.6° (*c* 0.9985, cyclohexane); and III (5.12%).

Thermal rearrangement of (−)-II *in acetonitrile.* A sample of (−)-II [15 mg in 150 μl acetonitrile; $[\alpha]^{25}_{578}$ − 90.9°, $[\alpha]^{25}_{365}$ − 293.2° (*c* 0.9061, cyclohexane)] was heated in a heavy-walled Pyrex tube for 4 hr at 217.8° ± 0.3°. Analysis gave only recovered II: $[\alpha]^{25}_{578}$ − 89.8°, $[\alpha]^{25}_{365}$ − 289.4 (*c* 0.7662, cyclohexane).

Acknowledgements—We express our gratitude to the Sanger Fund, to the Petroleum Research Fund administered by the American Chemical Society and to the Norman Fund in Organic Chemistry for their support of this work. To Prof. David Dixon, University of Minnesota go our special thanks for assistance with the calculation of the rate constants.

REFERENCES

[1] Antonietta Rose Mastrocola, *Stereoselectivity in the Thermal Rearrangement of Optically Active Cyclobutanes.* Ph.D. Dissertation, Harvard University, (1974); *Dissertation Abstracts International.* **35,** 5339-B (1975) (order no. 75-6574).[35]

[2] W. von E. Doering and K. Sachdev, *J. Am. Chem. Soc.* **96,** 1168–1187 (1974).

[3] L. Onsager, *Phys. Rev.* **37,** 405–426 (1931).

[4] W. von E. Doering and K. Sachdev, *J. Am. Chem. Soc.* **97,** 5512–5520 (1975).

[5a] J. A. Berson and P. B. Dervan, *Ibid.* **95,** 269–270 (1973); [b] J. A. Berson, P. B. Dervan, R. Malherbe and J. A. Jenkins, *Ibid.* **98,** 5937–5968 (1976); [c] Peter Brendan Dervan, *The Stereochemistry of the Thermal Rearrangements of* trans- *and* cis-1,2-*Dialkenylcyclobutanes.* Ph.D. Dissertation, Yale University (1973); *Dissertation Abstracts International* **33,** 130-B (1973) (order no. 73-16770).[35]

[6] P. H. Mazzocchi and H. J. Tamburin, *J. Am. Chem. Soc.* **92,** 7220–7221 (1970); *J. Org. Chem.* **38,** 2221–2222 (1973); *J. Am. Chem. Soc.* **97,** 555–561 (1975); [b] Henry John Tamburin, I., *Mechanistic Studies on the Thermal Vinylcyclopropane-cyclopentene Rearrangement.* Ph.D. Dissertation, University of Maryland (1971), *Dissertations Abstracts International* **32,** 5700-B (1972) (order no. 72-21859).[35]

[7] Edward Albert Barsa, *The Thermal Rearrangement of Substituted Cyclopropanes and the Stereochemistry of the Vinylcyclopropane Rearrangement.* Ph.D. Dissertation, Harvard University (1976); *Dissertation Abstracts International* **37,** 5077-B (1977) (order no. 77-9303).[35]

[8] W. von E. Doering and C. A. Guyton, *J. Am. Chem. Soc.* **100,** 3229–3230 (1978).

[9a] W. L. Dilling and R. D. Kroening, *Tetrahedron Letters* 695–698 (1970); [b] W. L. Dilling, *Chem. Rev.* **69,** 845–877 (1969).

[10] A. B. Chmurny and D. J. Cram, *J. Am. Chem. Soc.* **95,** 4237–4244 (1973).

[11] G. J. Janz and N. E. Duncan, *Ibid.* **75,** 5389–5392 (1953).

[12] J.-C. Soula, D. Lumbroso, M. Hellin and F. Coussemant, *Bull. Soc. Chim. (Fr.)* 2059–2065 (1966).

[13] G. B. Kistiakowsky and J. R. Lacher, *J. Am. Chem. Soc.* **58,** 123–133 (1936).

[14] B. Blankenburg, H. Fiedler, H. Hampel, H. G. Hauthal, G. Just, K. Kahlert, J. Korn, K.H. Müller, W. Pritzkow, Y. Reinhold, M. Röllig, E. Sauer, D. Schnurpfeil and G. Zimmermann, *J. prakt. Chem.* **316,** 804–816 (1974).

[15] G. D. Graham, Harvard-Chemistry, to be published elsewhere.

[16] B. Rickborn and F. R. Jensen, *J. Org. Chem.* **27,** 4606–4608 (1962).

[17] M. C. Lin and K. J. Laidler, *Trans. Faraday Soc.* **64,** 927–944 (1968).

[18] R. W. Vreeland and D. F. Swinehart, *J. Am. Chem. Soc.* **85,** 3349–3353 (1963).

[19] W. von E. Doering, G. Horowitz and K. Sachdev, *Tetrahedron* **33,** 273–283 (1977).

[20] W. von E. Doering and G. H. Beasley, *Ibid.* **29,** 2231–2243 (1973).

[21] J. D. Cox and G. Pilcher, *Thermochemistry of Organic and Organometallic Compounds.* Academic Press, New York (1970).

[22] G. Stridh, S. Sunner and Ch. Svensson, *J. Chem. Thermodynamics* **9,** 1005–1010 (1977).

[23] D. M. Brenner, *The Thermal Automerization of* 4-*Vinylcyclohexene.* Ph.D. Dissertation, Harvard University (1975); *Dissertation Abstracts International,* **36,** 5585–B (1976) (order no. 76-9930).[35]

[24] D. Rowley and H. Steiner, *Disc. Faraday Soc.* **10,** 198–213 (1951).

[25] E. R. Buchman, A. O. Reims, T. Skei and M. J. Schlatter, *J. Am. Chem. Soc.* **64,** 2696–2700 (1942).

[26] C. C. Schroff, W. S. Stewart, S. J. Uhm and J. W. Wheeler, *J. Org. Chem.* **36,** 3356–3361 (1971).

[27] J. R. Parikh and W. von E. Doering, *J. Am. Chem. Soc.* **89,** 5505–5506 (1967).

[28] R. Greenwald, M. Chaykovsky and E. J. Corey, *J. Org. Chem.* **28,** 1128–1129 (1963).

[29] W. von E. Doering, M. Franck-Neumann, D. Hasselmann and R. L. Kaye, *J. Am. Chem. Soc.* **94,** 3833–3844 (1972).

[30] R. B. Woodward and R. Hoffmann, *The Conservation of Orbital Symmetry.* Academic Press, New York (1970).

[31] J. E. Baldwin and C. Ullenius, J. Am. Chem. Soc. **96,** 1542–1547 (1974).

[32] J. A. Berson and L. Salem, *Ibid.* **94,** 8917–8918 (1972).

[33] H. C. Brown and B. C. Subba Rao, *Ibid.* **82,** 681–686 (1960).

[34] J. W. ApSimon, A. S. Y. Chau, W. G. Craig and H. Krehm, *Can. J. Chem.* **45,** 1439–1445 (1967).

[35] University Microfilms International, P.O. Box 1764, Ann Arbor, Michigan 48106.