

TRISECTION OF THE THERMAL AUTOMERIZATION OF 4-VINYLCYCLOHEXENE

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4-Vinylcyclohexene (I), the Diels-Alder and major product of the dimerization of butadiene, undergoes two degenerate thermal rearrangements which have been made visible by labelling with optical activity and deuterium.¹ In terms of the three processes of automerization, k_0 , k_1 and k_2 , shown in the figure, that work has revealed rearrangement of the vinyl group into the ring ($k_D = k_0 + k_2$) to be faster than loss of optical activity ($k_a = k_1 + k_2$). Since neither k_1 nor k_2 was evaluated, it followed only that $k_0 > k_1$ and that k_1 and k_2 could have any value lying between $(k_1 + k_2)$ and 0

Were the product of an incomplete automerization of optically pure I to be resolved into its optical antipodes and were each of these to be analyzed separately for the extent of isotope transposition, the three rate constants could be evaluated. These three processes bear on the role of concert and diradicals in bond-breaking and bond-remaking in 4-vinylcyclohexene

Optically active I, labelled in the C₂ methylene group with ¹⁴C, is prepared by an unexceptional sequence beginning with optically pure cyclohexene-4-carboxylic acid (II) [CH₂N₂, LiAlH₄, MsCl, LiBr, Na¹⁴CN, LiAlH₄, CH₃I, Ag₂O] Analysis involves the degradation of I to II [hydropyridinium perbromide in CH₂Cl₂, 5% EtOH at -86°, RuO₄ and NaIO₄ in acetone, Zn, CH₃COOH (overall yield 64%), resolution of II into R-(+)-II [brucine in CH₃COOEt] and S-(-)-II [(+)-*a*-phenylethylamine in acetone], and esterification [CH₂N₂] to the methyl ester (III) which is purified by glpc In this degradation, ¹⁴C is retained in rearranged products and lost from unrearranged products

Heating ¹⁴C-labelled I [$[a]_{365}^{25} -342.3^\circ$] at 380.2° for 2.0 hr yields I [$[a]_{365}^{25} -273.2^\circ$, 0.3667 ± 0.0010 μc/mmol], from which II [0.799 ± 0.006 optical purity, 0.888 ± 0.0005 μc/mmol (measured as III, A₀' in the sequel)] and S-(-)-III [>99% optical purity, 0.865 ± 0.005 μc/mmol (A₋)] are obtained. Attempts to recover R-(+)-II by resolution afforded a sample of S-(-)-III [0.391 ± 0.003 optical purity, 0.926 ± 0.0004 μc/mmol (measured as III, A₀ in the sequel)], enriched in R-(+)-III

The specific rate constants are derived by a two-step procedure. First, the rate constants for enantiomerization, $k_a = k_1 + k_2$, and transposition of label, $k_r = k_0 + k_2$, are calculated from the experimental data at $t = 7200$ sec by the equations in the earlier work¹ and are found to agree with that work within experimental error

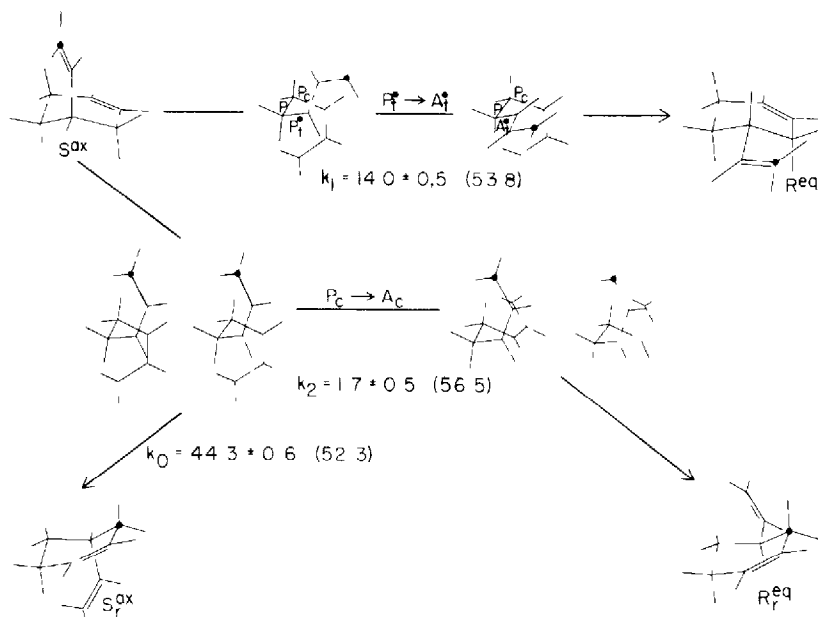
The specific radioactivity of (+)-III (A₊) (0.1065 μc/mmol) is calculated from A₀ and A₋ by the

equation $A_0 = nA_- + (1-n)A_+$, in which $2n - 1$ is the optical purity of II (0.799). Relative concentrations of products are calculated as percentages of I from the optical purity of II and the specific activities, A_+ and A_- .

Second, the trisection of k_d and k_T into k_0 , k_1 and k_2 is accomplished by optimization of k_2 with respect to the experimental ratio, $|R|/|R_T|$, the most sensitive measure of k_2 , by iterative integration of the four differential equations² defining the three reversible reactions. This procedure leads to the values, $k_2 = 1.7 \pm 0.9$ ($\pm 2\sigma$, the 95% confidence level), $k_0 = 44.3 \pm 0.6$ (σ) and $k_1 = 14.0 \pm 0.5$ (σ) $\times 10^{-6} \text{ sec}^{-1}$. Use of the data without attempted enrichment of R-(+)-II (A_0') gives $k_2 = 2.0 \pm 1.5$ (2σ) $\times 10^{-6} \text{ sec}^{-1}$. An early experiment with deuterium as the label afforded the value, $k_2 = 0.6 \pm 1.4$ (2σ) $\times 10^{-6} \text{ sec}^{-1}$.

Thus the existence of the k_2 process as a real but minor part of the reaction is established. From the order, $k_0 > k_1 > k_2$, the prediction, based on a freely rotating diradical (rotation much faster than reclosure), that $k_0 = k_1 = k_2$ is only 92% incorrect.

The two processes, k_1 and k_2 , unavoidably pass through a geometry in which the bonding orbitals are perpendicular to each other, cannot in theory be concerted, and will have transition states of energy equal to or greater than that of the hypothetical cis, trans-octa-2,7-dien-1,6-diyl diradical in its lowest energy form ($A_t^{\bullet} A A_c$)^{3,4,5}



Labelled carbon marked by •. Conformational specification follows Cahn, Ingold and Prelog.⁵ Specific rate constants ($\pm \sigma$) at 380 °C in 10^{-6} sec^{-1} (ΔG^\ddagger in kcal/mol). The two pairs of diradical, $P_C^{\bullet} P P_C$ and $P_C^{\bullet} P A_C$, in the middle lines are represented as stereoscopic pairs, the more easily to correlate the notation⁵ with the three-dimensional model.

One portion of the difference between k_1 and k_2 ($\Delta\Delta G^\ddagger = 2.7 \pm 0.5$ kcal/mol) is ascribed to the higher energy of the cis, cis configuration of the diradical (\bullet cis, cis \bullet) necessarily required by k_2 (the lower energy, \bullet cis, trans \bullet diradical suffices for k_1). We assign the conventional 1.0 kcal/mol increment to this thermodynamic factor, although without strong conviction.

The remaining portion of the difference is ascribed to a kinetic factor operating in the transition state. The rotational requirement for k_2 is economically expressed in terms of the rate-determining, continuous diradical as transition state² which couples the vibrational diradical⁶ ($P_C^\bullet P P_C$), associated with the C_3-C_4 bond-breaking levels of vinylcyclohexene in its axial, (cis, cis)-related conformation (S^{ax}), to the vibrational diradical ($P_C^\bullet P A_C$), associated with the C_6-C_1 bond-breaking levels of rearranged, enantiomeric vinylcyclohexene in its equatorial, (cis, cis)-related conformation (R_P^{eq}).⁷ This transition state is eclipsed and is characterized by substantial steric repulsion between (Z)-H-8 of the rotating, cis-allylic radical and (pS)-H-5.⁵ Accordingly the remaining 1.7 kcal/mol of the 2.7 ± 0.5 kcal/mol disadvantage of k_2 vis-à-vis k_1 is ascribed to the inherently greater barrier to this rotation of a cis-allylic radical ($P_C \rightarrow A_C$) compared to that of a trans-allylic radical ($P_t^\bullet \rightarrow A_t^\bullet$) (see figure).

Like k_2 , the process k_3 , whether or not concerted, requires a transition state having the cis, cis configuration. Unlike k_2 , k_3 requires no further discrete, energy-demanding internal rotation once the (family of) $P_C^\bullet P P_C$ vibrational diradical(s) has been reached: the average C_{2v} symmetry of this set defines a transition state common to S^{ax} and S_r^{ax} (no comparably simple coupling of S^{eq} to S_r^{eq} or S^{ax} to S_r^{eq} exists).

As a concerted process k_3 would involve a six-center Cope-type of transition state of the same C_{2v} symmetry as the related $P_C^\bullet P P_C$ diradical. The potential 22-kcal/mol concert estimated for the four-center Cope⁸ is essentially nullified by the 11-kcal/mol disadvantage of the six-center transition state⁹ and its bicyclo-[2.2.2]octane-like geometry (strain energy of 9.2 kcal/mol).¹⁰ Depending on whether the assignment of the entire incremental $\Delta\Delta G^\ddagger$ of 4.2 kcal/mol to an internal rotational barrier ($P_C \rightarrow A_C$) is correct, totally wrong or somewhere in between, the magnitude of concert would lie between 0 and 4.2 kcal/mol. Experimental uncertainty and the low, maximum value of the hypothetical concert prompts us to place k_3 into the class of "not obviously concerted" thermal rearrangements.

Formulation of the complete set of reaction paths in terms of the three sets of conformations of diradical structures (cis, cis, trans, trans [24 each] and cis, trans [27 members]),¹¹ the identification of individual structures as torsional-barrier protected or vibrational diradicals,⁶ and the entry of butadiene, cyclooctadiene, and cis and trans-divinylcyclobutane¹² into the set of reaction paths is deferred to later publications.

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REFERENCES AND NOTES

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- 3) Specification of the diradicals is based on the assumptions that conformational minima exist when the sp^2 - sp^3 bond is staggered and when the larger, C_2H_5 substituent of the sp^2 atom is staggered vis-à-vis the sp^3 atom.⁴ The system of Cahn, Ingold and Prelog⁵ is employed with the ad hoc modifications that designation of the labelled allylic moiety (e.g., P^*) precedes and that capital, A, is used in place of lower case, a, since "a" is the much-used abbreviation for antarafacial in discussions of thermal rearrangements
- 4) Although there is little uncertainty about assumption of a three-fold barrier to rotation about such an sp^2 - sp^3 bond, the question is open whether the staggered or eclipsed form represents the minimum [W. J. Orville-Thomas, ed., in Internal Rotation in Molecules, Wiley, New York, 1974]
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- 6) Those vibrational states concentrating an energy equal to or greater than that required to break a comparable acyclic bond are collectively defined as "vibrational" diradicals. Excluded from their definition is the inclusion of increments associated with overcoming barriers to internal rotation. The introduction of "vibrational" diradical leaves to "continuous" diradical the role of transition state, a) in the internal rotational coupling of two vibrational diradicals as in the k_1 and k_2 processes, b) when two apparently identical vibrational diradicals are involved as in the k_{12} process and c) in the coupling of a vibrational diradical to an "intermediary" diradical, which cannot reclose to a stable product without overcoming one or more barriers to internal rotation
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