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A Non-Cope among the Cope Rearrangements of 1,3,4,6-Tetraphenylhexa-1,5-dienes

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Abstract: The set of 1,3,4,6-tetraphenylhexa-1,5-dienes (**1**) represents a perturbation of Cope's rearrangement by four radical-stabilizing phenyl groups all positioned to drive the transition region toward the homolytic−colligative end of the mechanistic spectrum. The appearance of (*Z*)-isomers being suppressed thermodynamically by a steric interaction of +2.6 kcal mol^{-1} per cis double bond, an equilibration that is stereochemically not of any Cope type, emerges as the predominant reaction. It is an interconversion of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** (48:52; 77.3−115.3 °C) with the following values of the enthalpy, entropy, and volume of activation: $\Delta H^{\ddagger} = 30.7 \pm 0.2$ kcal mol^{-1}, $\Delta S^{\ddagger} = +2.1 \pm 0.4$ cal mol^{-1} K^{-1}, and $\Delta V^{\ddagger} = +13.5 \pm 0.1$ cm^{-3} mol^{-1}, respectively. Structures have been established by X-ray crystallographic analysis; a possible relationship between dihedral angle and bond lengths in the styrene portions is proposed. The entropy of activation is incompatible with a chair or boat Cope rearrangement; the volume of activation is neither low enough for a pericyclic Cope ("concerted") mechanism nor high enough for a homolytic−colligative mechanism involving full dissociation as the rate-determining step. Trapping and a crossover experiment give some but only partial support to the intermediacy of free radicals. At higher temperatures, however, electron spin resonance experiments demonstrate an equilibrium with kinetically free (*E*,*E*)-1,3-diphenylallyl radicals. These observations are rationalized in terms of geometric reorganization within the confines of a 'cage'. Resolution by chiral chromatography of ***rac*-(*E*,*E*)-1** allows recognition of a fast racemization (40−65 °C), of which $\Delta H^{\ddagger}$ (21.3 ± 0.1 kcal mol^{-1}), $\Delta S^{\ddagger}$ (−13.2 ± 0.3 cal mol^{-1} K^{-1}), and $\Delta V^{\ddagger}$ (−7.4 ± 0.4 cm^{-3} mol^{-1}) are consistent with a pericyclic Cope rearrangement. Enriched (*Z*)-isomers undergo Cope rearrangements in accord with the known influence of axiality and the chair/boat alternative on the energy of the transition region.

Introduction

Following the announcement of the long since eponymous rearrangement of hexa-1,5-dienes by Arthur C. Cope in 1940,[1] many attempts to gain intellectual control of a predictive value over this erstwhile 'no-mechanism' reaction have appeared. Central to an understanding is the response of the archetype to structural perturbations. In this paper, perturbation by phenyl groups is pursued to its end by examining the family of six 1,3,4,6-tetraphenylhexa-1,5-dienes (**1**).[2,3] These four positions of substitution are 'active' positions by analogy with the 1- and 3-positions of the allyl radical in that substituents occupying

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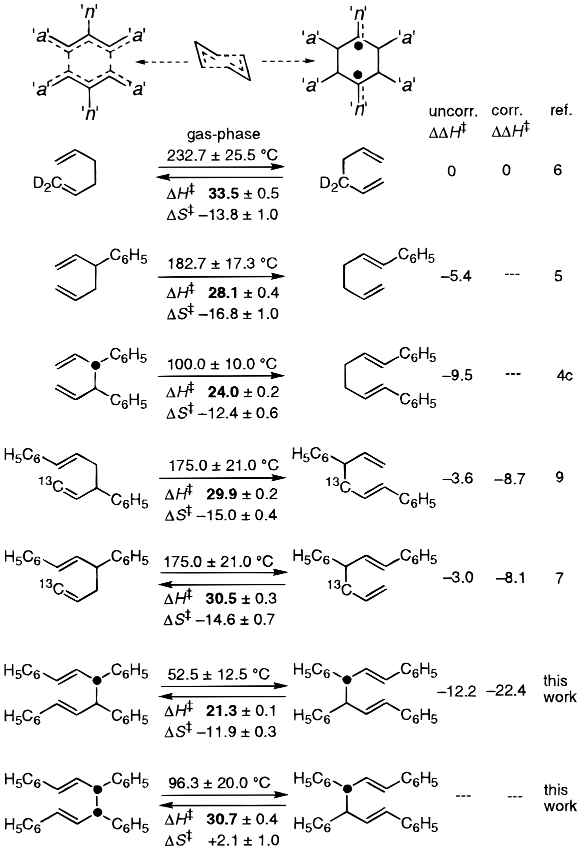

Figure 1. Temperature ranges over which kinetic data is gathered, and derived Eyring activation parameters for various hexa-1,5-dienes substituted by phenyl groups in 'active' ('a') positions are shown. Differences in enthalpies of activation between hexa-1,5-diene, the archetype, as reference are tabulated, uncorrected, and corrected for decelerating conjugative interaction in the educt.

these positions may exercise their radical-stabilizing capacity optimally in contrast to those in the 'nodal' 2-position.

The history of the perturbation of the Cope rearrangement by phenyl substitution in active positions began with the exploration by Koch of 3,4-diphenylhexa-1,5-diene as a candidate for rearrangement by a nonconcerted mechanism of the homolytic−colligative type.[4a] Although this conjecture at first seemed to have found support in the purported isolation of 1,4-diphenylhexa-1,5-diene, it was later proved incorrect by Lutz and co-workers, the products having been the 1,6-diphenylhexa-1,5-dienes expected of a pericyclic mechanism.[4b] These workers found an enthalpy of activation ($\Delta H^\ddagger$) for the rearrangement of *rac*-3,4-diphenylhexa-1,5-diene lower than that of the archetype by −9.5 kcal mol^{-1} (Figure 1).[4c] Its concerted nature received strong support through the high-pressure studies of Klärner and co-workers.[4d]

The story developed further with the experimental and theoretical work of Dewar et al. on mono- and diphenyl derivatives, including 3-phenylhexa-1,5-diene.[5] This compound rearranged with an enthalpy of activation −5.4 kcal mol^{-1} lower than that of the archetype.[6] Consistently, 1,3-diphenylhexa-1,5-diene had a $\Delta H^\ddagger$ lower by −8.1 kcal mol^{-1},[7] after correction by −5.1 kcal mol^{-1} for conjugative interaction in the educt.[8] 1,4-Diphenylhexa-1,5-diene underwent a similar rearrangement[9] with a $\Delta H^\ddagger$ lower than that of the archetype by −8.7 kcal mol^{-1}, again after correction by −5.1 kcal mol^{-1} for the stabilizing effect of conjugative interaction on the educt. In summary, two phenyl groups in active positions of hexa-1,5-diene appear to lower the energy of the transition region by −8.8 ± 0.7 kcal mol^{-1} (−4.4 kcal mol^{-1} per phenyl group).

Were all four active sites to be occupied by phenyl groups, reaction by the homolytic−colligative mechanism might become a credible possibility.[10,11] Whether four phenyl groups (−17.6 kcal mol^{-1}) could be expected to match the 26 kcal mol^{-1} difference between the bond dissociation energy of hexa-1,5-diene[12] and the $\Delta H^\ddagger$ of its degenerate Cope rearrangement remained a source of scepticism. None the less, the radical-stabilizing power of the perturbation promised to be larger than any other in the literature,[13] with the possible exception of the nodally substituted 2,5-diphenylhexa-1,5-diene.[5b,14]

Results

1,3,4,6-Tetraphenylhexa-1,5-dienes (1). Compounds of constitution **1** have already been prepared by Bergmann and Ukai,[15] by Vögtle and Goldschmitt in racemic and meso configuration,[16] and by Boche and Schneider as mixtures of diastereomers of the various geometric configurations.[17] Starting either with chalcone or 1,3-diphenylpropene, ***rac*-(*E*,*E*)-1** of mp 143 °C and ***meso*-(*E*,*E*)-1** of mp 138 °C are conveniently prepared as a mixture separable by a combination of crystallization and manual segregation.

***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** crystallize in a noncentrosymmetric ($P2_12_12$) and a centrosymmetric ($P\bar{1}$) space group, respectively. Quite unusually, only a single enantiomer is seen in the crystal of ***rac*-(*E*,*E*)-1**, thus indicating the noncentrosym-

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(1) (a) Cope, A. C.; Hardy, E. M. *J. Am. Chem. Soc.* **1940**, *62*, 441−444. (b) Cope, A. C.; Hoyle, K. E.; Heyl, D. *J. Am. Chem. Soc.* **1941**, *63*, 1843−1852. (c) Cope, A. C.; Hofmann, C. M.; Hardy, E. M. *J. Am. Chem. Soc.* **1941**, *63*, 1852−1857. (d) Whyte, D. E.; Cope, A. C. *J. Am. Chem. Soc.* **1943**, *65*, 1999−2004. (e) Levy, H.; Cope, A. C. *J. Am. Chem. Soc.* **1944**, *66*, 1684−1688. (f) Foster, E. G.; Cope, A. C.; Daniels, F. *J. Am. Chem. Soc.* **1947**, *69*, 1893−1896.

(2) For the only previous investigation of a 1,3,4,6-tetrasubstituted hexa-1,5-diene, see the elegant, painstaking work of Gajewski, Benner, and Hawkins on 4,5-dimethylocta-2,5-dienes.[3]

(3) Gajewski, J. J.; Benner, C. W.; Hawkins, C. M. *J. Org. Chem.* **1987**, *52*, 5198−5204.

(4) (a) Koch, H. P. *J. Chem. Soc.* **1948**, 1111−1117. (b) Lutz, R. P.; Bernal, S.; Harris, R. O.; McNicholas, M. W. *J. Am. Chem. Soc.* **1971**, *93*, 3985−3990. (c) Lutz, R. P.; Berg, H. A. J. *J. Org. Chem.* **1980**, *45*, 3915−3916. (d) Diedrich, M. K.; Hochstrate, D.; Klärner, F.-G.; Zimny, B. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1079−1081.

(5) (a) Dewar, M. J. S.; Ford, G. P.; McKee, M. L.; Rzepa, H. S.; Wade, L. E., Jr. *J. Am. Chem. Soc.* **1977**, *99*, 5069−5073. (b) Dewar, M. J. S.; Wade, L. E., Jr. *J. Am. Chem. Soc.* **1977**, *99*, 4417−4424.

(6) Doering, W. von E.; Toscano, V. G.; Beasley, G. H. *Tetrahedron* **1971**, *27*, 5299−5306.

(7) Doering, W. von E.; Wang, Y.-h. *J. Am. Chem. Soc.* **1999**, *121*, 10112−10118.

(8) Doering, W. von E.; Benkhoff, J.; Carleton, P. S.; Pagnotta, M. *J. Am. Chem. Soc.* **1997**, *119*, 10 947−10 955.

(9) Doering, W. von E.; Birladeanu, L.; Sarma, K.; Teles, J. H.; Klärner, F.-G.; Gehrke, J.-S. *J. Am. Chem. Soc.* **1994**, *116*, 4289−4297.

(10) Dissociation of hexa-1,5-diene into two allyl radicals is also an example of reaction by the *intermolecular* homolytic−colligative mechanism,[12] as is the observation that 1,4-diphenylhexa-1,5-diene is converted to 1,6-diphenylhexa-1,5-diene at high temperature.[9] There are several examples of the oxymoronic *intramolecular* homolytic−colligative type; that is, Cope rearrangements proceeding in two steps by way of a diradical (not two radicals) as intermediate.[11]

(11) Among numerous examples, see Roth, W. R.; Gleiter, R.; Paschmann, V.; Hackler, U. E.; Fritzsche, G.; Lange, H. *Eur. J. Org. Chem.* **1998**, 961−967.

(12) Roth, W. R.; Bauer, F.; Beitat, A.; Ebbrecht, T.; Wüstefeld, M. *Chem. Ber.* **1991**, *124*, 1453−1460.

(13) Cope rearrangements of the 1,2-divinylcyclopropane and cyclobutane types have a well-known history in which both concerted and nonconcerted paths are strongly accelerated by relief of a strain energy of ~26 kcal mol^{-1}.

(14) Roth, W. R.; Lennartz, H.-W.; Doering, W. v. E.; Birladeanu, L.; Guyton, C. A.; Kitagawa, T. *J. Am. Chem. Soc.* **1990**, *112*, 1722−1732.

(15) Bergmann, E.; Ukai, T. *Chem. Ber.* **1933**, *66*, 54−58.

(16) Vögtle, F.; Goldschmitt, E. *Chem. Ber.* **1976**, *109*, 1−40.

(17) Boche, G.; Schneider, D. R. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 869−870.

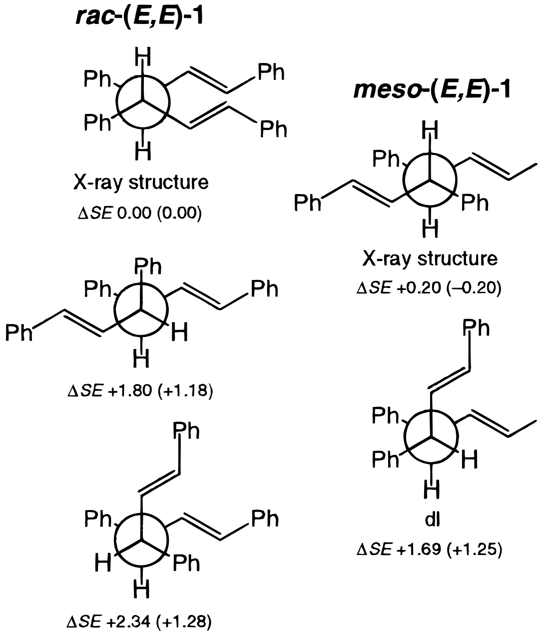
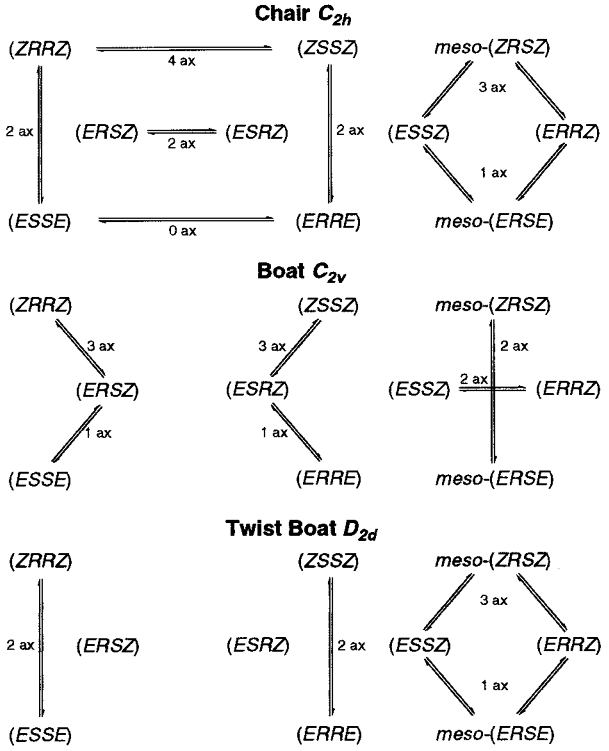


Figure 2. Crystallographic structures of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** are shown along with their other staggered conformations. Differences in steric energies (ΔSE in kcal mol^{-1} as calculated by MM2 (MM3) [***rac*-(*E*,*E*)-1**: −11.71 kcal mol^{-1} (41.63 arbitrary units)] are given.

metric structure and a spontaneous resolution.[18] Extensive efforts to exploit this phenomenon for preparative resolution of ***rac*-(*E*,*E*)-1** have been unsuccessful. The absolute structure cannot be determined because the anomalous dispersion of hydrocarbons is too low. Because both structures are arranged around crystallographic symmetry elements (an inversion center within the central single bond of ***meso*-(*E*,*E*)-1** and a 2-fold axis passing through the central single bond of ***rac*-(*E*,*E*)-1**), the molecules have crystallographic C_i and C_2 symmetry, respectively (Figure 2). Crystallographic data and Ortep representations are available in Item SI-1 and Figure SI-1, respectively, of the Supporting Information. The dihedral angles between the phenyl group and double bond are 11.2° in ***meso*-(*E*,*E*)-1** and 23.7° in ***rac*-(*E*,*E*)-1**. In both, the central hydrons of the C3−C4 bond are in the antiperiplanar conformation rather than the synclinal conformation more commonly seen in 1,2-tetrasubstituted ethanes with bulky substituents.[19] The antiperiplanar conformations concur with expectations based on the differences in steric energies calculated by molecular mechanical methods (MM2[20] and MM3[21]). Further discussion of the data, particularly of the ratio of the length of the conjugated single bond between double bond and phenyl, and the length of the double bond, as a function of dihedral angle is given in the Appendix.

At temperatures ∼100 °C, ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** are interconverted, ultimately reaching equilibrium (48:52). This equilibration has already been noted by Vögtle and Goldschmitt at 200 °C,[16] and by Perkins and co-workers at 80 °C after boiling in benzene for 60 h,[22] but without comment from either group. With the exception of the example of Gajewski, Benner, and Hawkins,[3] and that uncovered recently by Rüchardt and co-workers in 3,4-di(1-cyclohexen-1-yl)-2,2,5,5-tetramethylhexa-1,5-diene,[23] the interconversion is almost unprecedented. It cannot be accommodated by any concatenation of the three sets of conventional chair, boat, or twist-boat Cope rearrangements (Scheme 1). In the boat domain, for example, ***rac*-(*E*,*E*)-1** (ESSE/ERRE) can rearrange to ***meso*-(*E*,*Z*)-1** (ESRZ or ERSZ), but then finds itself in a cul-de-sac in the chair or twist-boat domain unable to reach ***meso*-(*E*,*E*)-1**. The interconversion of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** may be constitutionally of the Cope type, but configurationally it is not.

Scheme 1



Elucidation of the kinetics is an essential element in trying to understand the mechanism of this atypical interconversion. That the reaction is first-order is confirmed by the failure of a 10-fold increase in concentration to change the rate. Kinetics are followed from either ***meso*-** or ***rac*-(*E*,*E*)-1** over the temperature range, 77.3−115.3 °C. A few percent of the two (*E*,*Z*)-isomers (vide infra), disfavored by +2.6 kcal mol^{-1} per double bond,[8] are also formed, but so much more rapidly that they constitute a preequilibrium of no deleterious consequence for determination of the kinetics. A sample of experimental data at 101 °C is given in Table SI-1. Specific rate constants and activation parameters are summarized in Table 1: $\Delta H^{\ddagger} = 30.7 \pm 0.4$ kcal mol^{-1}, and entropy of activation ($\Delta S^{\ddagger}$) $= +2.1 \pm 1.0$ cal mol^{-1} K^{-1}. If a $\Delta H^{\ddagger}$ slightly lower than that of the archetype (Figure 1) occasions no surprise, the $\Delta S^{\ddagger}$, being much more positive than that of the archetype (-13.8 ± 1.0 cal mol^{-1} K^{-1}), is not only strikingly inconsistent with a mechanism of the concerted, pericyclic type, but is also significantly smaller than would be expected of a process involving dissociation into a pair of free radicals as the rate-determining step.

Free (*E*,*E*)-1,3-diphenylallyl radicals by homolysis constituted such an attractive hypothesis to explain the non-Cope-like stereochemistry that extensive efforts were mounted to determine what role, if any, they might be playing. Electron spin resonance

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(18) Brock, C. P.; Dunitz, J. D. *Chem. Mater.* **1994**, *6*, 1118−1127.

(19) Structural assignments are reversed in ref 17.

(20) Burkert, U.; Allinger, N. L. *Computational Chemistry*; American Chemical Society: Washington, DC, 1982. Cambridge Scientific Computing, Inc., Cambridge, MA 02139: Chem 3D 3.0.1.

(21) Allinger, N. L.; Yuh, Y. H.; Lii, J.-H. *J. Am. Chem. Soc.* **1989**, *111*, 8551−8566.

(22) Corbally, R. P.; Perkins, M. J.; Elnitski, A. P. *J. Chem. Soc., Perkin Trans. 1* **1979**, 793−798.

(23) Herberg, C.; Beckhaus, H.-D.; Körtvelyes, T.; Rüchardt, C. *Chem. Ber.* **1993**, *123*, 117−127.

Table 1. Specific Rate and Equilibrium Constants and Activation Parameters for the Thermal Interconversion of *rac*- and *meso*-(*E*,*E*)-1,3,4,6-Tetraphenylhexa-1,5-diene [***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1**] in Benzene-d_6

T, °C	$k_1{}^a$	$k_{-1}{}^a$	K^b
77.3 ± 0.14^c	1.47 ± 0.01	1.31 ± 0.01	1.12
80.7 ± 0.28^c	2.25 ± 0.02	2.02 ± 0.02	1.11
87.2 ± 0.15^d	5.28 ± 0.04	4.77 ± 0.04	1.11
101.4 ± 0.14^c	26.9 ± 0.15	24.6 ± 0.14	1.10
101.4 ± 0.14^e	27.0 ± 0.5	24.6 ± 0.5	1.10
110.5 ± 0.11^c	74.3 ± 0.3	68.2 ± 0.3	1.09
115.3 ± 0.09^c	118.2 ± 0.9	109.3 ± 0.9	1.08

Arrhenius plot [$1/T$ vs log k]
$E_a = 31.44 \pm 0.37$ kcal mol$^{-1\,f}$
log $A = 13.78 \pm 0.22^f$
Eyring parameters^g
$\Delta H^\ddagger = 30.7 \pm 0.4$ kcal mol$^{-1\,f}$
$\Delta S^\ddagger = +2.1 \pm 1.0$ cal mol^{-1} K$^{-1\,f}$
thermodynamics [$1/T$ vs log K]
$\Delta H = -0.22 \pm 0.02$ kcal mol^{-1}
$\Delta S = -0.40 \pm 0.06$ cal mol^{-1} K^{-1}

[a] Calculated by linear regression of the usual expression for a reversible first-order reaction: $(x - x_o)/(x_e - x_o) = \exp[-(k_1 + k_{-1})t]$; s = standard error; rate constants in units of 10^{-6} s^{-1}. [b] The equilibrium constant, $K = k_1/k_{-1}$. [c] 0.0278 M in ***rac*-(*E*,*E*)-1**; 0.00213 M in 18-crown-6 ether. [d] 0.020 M in ***rac*-(*E*,*E*)-1**; 0.00125 M in 18-crown-6 ether. [e] 0.0275 M in ***meso*-(*E*,*E*)-1**; 0.002 M in 18-crown-6 ether. [f] 95% confidence limits. [g] Calculated at 96.3 °C.

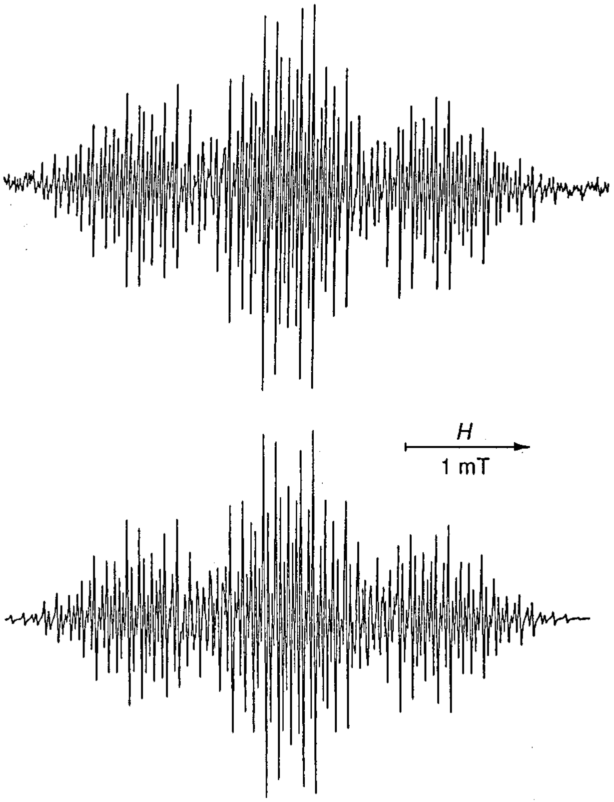

Figure 3. The upper ESR spectrum is that of the (*E*,*E*)-1,3-diphenylallyl radical generated by thermal dissociation of *meso*-(*E*,*E*)-1,2,3,4-tetraphenylhexa-1,5-diene in diphenyl ether at 251 °C. The lower spectrum is the computer-simulated (overall width 44.93 *g*) using the hyperfine splitting constants [*g*] in Figure 4.

(ESR) spectroscopy was accordingly applied in the hope of observing the free radical directly. A solution of ***meso*-(*E*,*E*)-1** in diphenyl ether at 251 °C revealed a spectrum (Figure 3) that could be simulated by computer (overall width 44.93 g) using the hyperfine splitting constants (*g*) in Figure 4 (*g* value = 2.00269). 1,3-Diphenylallyl was identified essentially unambiguously as a radical of symmetrical structure, almost certainly of the (*E*,*E*) rather than the (*Z*,*Z*) configuration. Splitting constants for tetraphenylallyl radical[24a] and cinnamyl radical[24b] are shown for purposes of comparison. Attempts to obtain thermodynamic quantities from the temperature dependence of equilibrium constants observed over the temperature range 200−300 °C were only partially successful, because additional, if smaller, lines appeared at higher temperatures on the outer wings of the spectra. At temperatures >270 °C, the fit of signal amplitudes was even less satisfactory, suggestive of increasing contamination by other radicals, probably (*E*,*Z*)-1,3-diphenylallyl. To extract the hyperfine splitting constants for the minor isomer was impossible because each phenyl group was expected to exhibit different splittings. In the absence of knowledge of the temperature dependence of the concentration of the minor isomer, precise determinations could not be made. Beyond that impediment, slopes of the intensities of the ESR spectra for uphill and downhill variation of temperature diverged markedly, which indicated significant irreversible chemical change at the higher temperatures (persistent yellowing). Best efforts with the equilibrium constants (to be found in Item SI-2) led to the following values of enthalpy and entropy for the reaction: $\Delta H_r = 32.3 \pm 5.3$ kcal mol^{-1} and $\Delta S_r = +17.1 \pm 9.8$ cal mol^{-1} K^{-1}, respectively. Although the precision of the bond dissociation energy (BDE) is insufficient to conclude that a homolytic−colligative mechanism is operative, the BDE range encompasses the $\Delta H^\ddagger$ of the non-Cope interconversion and thus admits the free radical as an energetically credible intermediate.

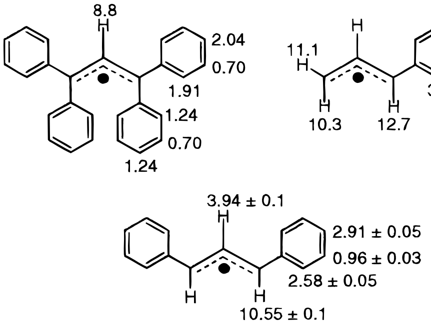

Figure 4. Hyperfine splitting constants (*g*) of the 1,1,3,3-tetraphenylallyl radical (top left),[24a] cinnamyl radical (top right),[24b] and the (*E*,*E*)-1,3-diphenylallyl radical (bottom) are given.

Several experiments undertaken to block the interconversion by traps for free radicals led to ambiguous results and weakened the case for a homolytic−colligative mechanism. These efforts involved phenol, 9,10-dihydroanthracene, 2,2,6,6-tetramethylpiperidinyl oxyl (TEMPO), oxygen at atmospheric pressure, and 2-methyl-2-nitrosopropane, none of which either inhibited or diverted the interconversion.[25] High concentrations of thiophenol did generate substantial amounts of 1,3-diphenylpropene as well as the product of addition with thiophenol. In the presence of low concentrations of thiophenol, the interconversion continues to be observed. Further details may be found in the Experimental Section and Item SI-3. It may be tentatively concluded that some, but not all, of the rearrangement proceeds by way of free 1,3-diphenylallyl radicals.

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(24) (a) Landolt-Bernstein, New Series, *Magnetic Properties of Free Radicals*, Vol. II/17cb; Fischer, H., Hellwege, K. H., Eds.; Springer: Berlin, 1989; p 25 ff; (b) Landolt-Bernstein, New Series, *Magnetic Properties of Free Radicals*, Vol. II/9b; Fischer, H., Hellwege, K. H., Eds.; Springer: Berlin, 1977; p 392.

(25) An energetically implausible chain mechanism involving 1,3-diphenylallyl radical as carrier finds no support in the failure of additions of AIBN or iodine to accelerate the reaction.

The late Wolfgang Roth has applied his powerful method of trapping in supercritical carbon dioxide with high partial pressures of oxygen.[26] Quantitative examination has revealed three distinct processes. At low partial pressures (∼1−2 kbar) of oxygen, there is a dramatic reduction in the rate constant of the interconversion of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** to about half its oxygen-free value. As pressures are increased up to ∼90 kbar, this rate constant suffers no further decrease, but disappearance of educt continues to increase. In their model for rationalizing these observations, three intermediate complexes are hypothesized: one engaging in the interconversion with no interference by oxygen; a second being the precursor of the kinetically free free-radicals thought to be rapidly trapped at the low oxygen pressures; and a third leading irreversibly to byproducts in a second-order reaction with oxygen. Critical examination of this model has not been possible because of the absence of primary experimental data. Whether the results would be significantly different in solution will be difficult to determine because of the generally very low solubility of oxygen in organic solvents.

Crossover experiments are the classical device to establish mechanisms of the homolytic−colligative, dissociative−recombinative type. Of two experimental designs, both involving dissociation into two different intermediates (the one starting from a single, unsymmetrically substituted reactant and the other from two symmetrically but differently substituted reactants), we have chosen to start from a mixture of the phenyl compounds (**1**) and their *p*-tolyl analogues (**2**). Mass spectroscopy was the analytical method.

Preparation following one of the procedures used for **1** gives rise to two crystalline compounds, which are assumed to be ***meso*-** and ***rac*-(*E*,*E*)-2**, although no effort has been made to distinguish between them (experimental details in Item SI-4). The structure ***meso*-(*E*,*E*)-2** is assigned to the less soluble isomer solely by analogy to ***meso*-(*E*,*E*)-1**. When an equimolar mixture of ***meso*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-2** is heated in toluene-d_8 at 110 °C for 13.5 h, a new set of peaks centered at *m*/*e* 414 in the mass spectrum appears, in addition to those at 386 and 442, which correspond to the starting hexadienes. This period of heating corresponds to ∼10 half-lives in the interconversion of **(*E*,*E*)-1**. Instead of the statistically expected ratios of 1.00:***2.00***:1.00, ratios of 0.93:***0.57***:1.00 are obtained. Although some crossover has occurred in support of the involvement of 1,3-diphenylallyl radicals, convincing support for the *exclusive* operation of the homolytic−colligative mechanism is not forthcoming. This result is consistent with those from the trapping experiments already outlined: free radicals appear to be playing some role in the rearrangement, but most of the reaction seems to be occurring by nondissociative paths.

Deeper insight can be gained by examination of the pressure dependence. Competing pericyclic and stepwise rearrangements having been shown to respond very differently to variation in pressure,[27] application of high pressure is now accepted to be a penetrating method for probing the pericyclic nature of rearrangements of the Cope and electrocyclic types.[4d] The thermal rearrangement of *cis*- and *trans*-1,2-divinylcyclobutane to 1,5-cyclooctadiene is an unambiguous example. The cis isomer is accelerated by an increase in pressure [volume of activation ($\Delta V^{\ddagger}$) = −14.1 cm^3 mol^{-1} at 69.8 °C] consistent with the operation of a pericyclic Cope mechanism, whereas the trans isomer is retarded and shows a positive $\Delta V^{\ddagger}$ (+4.1 cm^3 mol^{-1} at 159.6 °C).[9] A homolytic−colligative mechanism is expected to show a deceleration of rate and a positive volume of activation. The partial molar volumes of cyclic transition states, determined within the scope of the Eyring transition-state theory as the sum of the activation volume and partial molar volumes of the reactants, are consistently smaller than those of the corresponding acyclic transition states as a consequence of larger packing coefficients.[28]

Table 2. Effect of Pressure on the Thermal Interconversion of ***meso*-(*E*,*E*)-1** (**M**) and ***rac*-(*E*,*E*)-1** (**R**) at 98 °C for 96 h in Toluene-d_8 and Benzene-d_6

p, bar	solvent	(**M**) → (**R**)	(**R**) → (**M**)
1	C_7D_8	53:47	48:52
1	C_6D_6	54:46	48:52
10 500	C_7D_8[a]	91:09	89:11
10 500	C_6D_6[b]	99:01	95:05

[a] Liquid: T_f of toluene is 30 °C at 9600 bar. [b] Crystalline: T_f of benzene is 114 °C at 5100 bar.

The effect of increasing pressure on the interconversion of ***meso*-(*E*,*E*)-1** and ***rac*-(*E*,*E*)-1** is striking. In toluene at 10.5 kbar, where still a liquid, the rate is significantly slower than at 1 bar (cf. rows 1 and 3, Table 2). In benzene at 10.5 kbar, where the compounds are now in a crystalline matrix, the interconversion is almost completely suppressed (at 1 bar, same rate as in toluene). From the pressure dependencies of the specific rate constants available in Table SI-2, values of $\Delta V^{\ddagger}$ are derived for the forward reaction ($\Delta V^{\ddagger} = +13.5 \pm 0.1$ cm^3 mol^{-1}) and the reverse reaction ($\Delta V^{\ddagger} = +11.5 \pm 0.2$ cm^3 mol^{-1}). The difference in the activation volumes of the reaction ($\Delta\Delta V_r = -2.0$ cm^3 mol^{-1}) should equal the volume of *reaction* and indeed is in good agreement with the value derived from measurements of changes in partial molar volumes ($\Delta\Delta V_r = -1.7$ cm^3 mol^{-1}; see Experimental Section and Table SI-3). These positive $\Delta V^{\ddagger}$ values are sharply inconsistent with a cyclic transition state and point to a large expansion of volume in the transition state in *qualitative* accord with dissociation. A good estimate of the volume change for reaction to a pair of independently free 1,3-diphenylallyl radicals can be made with Exner increments.[29,30] The partial molar volume of ***meso*-(*E*,*E*)-1** or ***rac*-(*E*,*E*)-1** is calculated to be 349.7 cm^3 mol^{-1} (related to 20 °C), which is in agreement with the values of 345.7 and 351.7 cm^3 mol^{-1}, respectively, already determined from density measurements. The calculated partial molar volume of the 1,3-diphenylallyl radical is 186.7 cm^3 mol^{-1}, whence is derived a volume of reaction of +23.7 cm^3 mol^{-1}, which is almost twice as large as the experimental $\Delta V^{\ddagger}$ values already mentioned. The ground state is certainly not moving toward a tight cycle ($\Delta V^{\ddagger}$ in the range of −12 cm^3 mol^{-1}), but rather toward an extended system, the $\Delta V^{\ddagger}$ of which *quantitatively* falls short of that expected of a rate-determining transition region resembling solvent-separated free radicals. Compare, for example, the high

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[26] Roth, W. R.; Hunold, F. *Liebigs Ann.* **1996**, 1917−1928. Hunold, F. Ph.D. Dissertation, Ruhr-Universität Bochum: "Bildung und Rekombination konjugativ stabilisierter Radikale; Analyse durch Sauerstoffabfang in überkritischem CO$_2$", Shaker Verlag: Postfach 1290, D-52013 Aachen, Germany.

[27] Klärner, F.-G. *Chem. Uns. Zeit* **1989**, *23*, 53−63. Klärner, F.-G.; Krawczyk, B.; Ruster, V.; Deiters, U. K. *J. Am. Chem. Soc.* **1994**, *116*, 7646−7657. Klärner, F.-G.; Diederich, M. K.; Wigger, A. E. Effect of Pressure on Organic Reactions. In *Chemistry under Extreme or Nonclassical Conditions*; van Eldik, R., Hubbard, C. D., Eds; Wiley: New York, Spektrum: Heidelberg, 1997; Chapter 3, pp 103−161.

[28] The packing coefficient, η, is defined as the ratio between the intrinsic volume, the so-called van der Waals volume, and the partial molar volume ($\eta = V_W/V$): Asano, T.; le Noble, W. J. *Rev. Phys. Soc. Jpn.* **1973**, *43*, 82−91. Yoshimura, Y.; Osugi, J.; Nakahara, M. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 680−683. Yoshimura, Y.; Osugi, J.; Nakahara, M. *J. Am. Chem. Soc.* **1983**, *105*, 5414−5418.

[29] Exner, O. In *Organic High-Pressure Chemistry*; le Noble, W. J., Ed.; Elsevier: Amsterdam, 1988; pp 19−49.

Table 3. Specific Rate Constants and Activation Parameters for Thermal Racemization of (+)-(*E*,*E*)-1,3,4,6-Tetraphenylhexa-1,5-diene [**(+)-(*E*,*E*)-1**] in *n*-Hexane/2-Propanol (70/30)

T, °C	$k_{rac}{}^{a}$
40.0	2.19 ± 0.01
45.1	3.82 ± 0.05
55.1	10.93 ± 0.07
55.0[b]	10.50 ± 0.14
65.0	29.82 ± 0.21

Arrhenius plot [$1/T$ vs $\log k$]
$E_a = 21.98 \pm 0.09$ kcal mol^{-1}
$A = (4.74 \pm 0.71) \times 10^{10}$ s^{-1}
Eyring parameters[c]
$\Delta H^{\ddagger} = 21.3 \pm 0.1$ kcal mol^{-1}
$\Delta S^{\ddagger} = -11.9 \pm 0.3$ cal mol^{-1} K^{-1}

[a] Calculated by linear regression using equation, $k_{rac} = (1/t) \times \ln(ee_o/ee_t)$; all standard errors are 95% confidence level; rate constants in units of 10^{-5} s^{-1}. [b] This experiment starts with (−)-(*E*,*E*)-1,3,4,6-tetraphenylhexa-1,5-diene. [c] Calculated at 52.5 °C.

positive $\Delta V^{\ddagger}$ (+35.7 cm^3 mol^{-1}) observed in the thiophenol-trapped dissociation of 3,4-diethyl-3,4-diphenylhexane.[31] These efforts have not established free radicals as a sufficient explanation of the non-Cope interconversion. The various observations taken together will be discussed later in terms of a caged radical pair.

Pericyclic Cope Rearrangements of 1. The conventional Cope rearrangements open to the configurational isomers of **1** in the chair, boat, and twist−boat conformations have been brought together in Scheme 1. Enantiomerizations of ***rac*-(*E*,*E*)-1** in the chair, and a nonreaction of ***meso*-(*E*,*E*)-1** in the boat conformation, are distinguished by allowing all four phenyl groups to occupy 'equatorial' positions in the transition region,[32] and are therefore likely the fastest of the conventional Cope rearrangements in this series. Resolution of ***rac*-(*E*,*E*)-1** into its pure enantiomers has been effected efficiently by high-performance liquid chromatography (HPLC) on a chiral column. Racemization is already rapid by 40 °C. From the time dependence of the enantiomeric ratios determined at four temperatures between 40 and 65 °C (Table 3), activation parameters can be obtained: $\Delta H^{\ddagger} = 21.3 \pm 0.1$ kcal mol^{-1} and $\Delta S^{\ddagger} = -11.9 \pm 0.3$ cal mol^{-1} K^{-1}. The $\Delta H^{\ddagger}$ is among the lowest recorded, whereas the negative $\Delta S^{\ddagger}$ is fully consistent with the operation of a pericyclic Cope mechanism.

Further to confirm the pericyclic nature of the enantiomerization, its $\Delta V^{\ddagger}$ value was determined from the pressure dependence of the rate constants of racemization of **(−)-(*E*,*E*)-1** (Table 4). At the same time, the pressure dependence of another strongly stabilized, degenerate, pericyclic rearrangement of comparably low $\Delta H^{\ddagger}$, that of 2,5-diphenylhexa-1,5-diene-1,6-^{13}C, was also examined (Table SI-4). These $\Delta V^{\ddagger}$ values and two others already in the literature[4d,9] are collected in Figure 5. Although they have not been related to the same temperature, the $\Delta V^{\ddagger}$ values are all negative and in the range of −9 to −13 cm^3 mol^{-1}. The negative $\Delta V^{\ddagger}$ observed for the racemization of **(*E*,*E*)-1** ($\Delta V^{\ddagger} = -7.4$ cm^3 mol^{-1}) is thus quite compatible with a pericyclic mechanism.

Table 4. Pressure Dependence of Specific Rate Constants for Thermal Racemization of (−)-(*E*,*E*)-1,3,4,6-Tetraphenylhexa-1,5-diene [**(−)-(*E*,*E*)-1**] at 44.3 °C in *n*-Hexane/2-Propanol (70/30)

p, bar	$k_{rac}{}^{a}$
1	3.52 ± 0.03[b]
250	3.84 ± 0.02
500	4.12 ± 0.05
1000	4.68 ± 0.03
2000	5.44 ± 0.03
3000[b]	6.38 ± 0.06
4000	7.08 ± 0.08

$\Delta V^{\ddagger} = -(7.4 \pm 0.4)$ cm^3 mol^{-1} [c]
$\Delta V^{\ddagger} = -(7.1 \pm 0.1)$ cm^3 mol^{-1} [d]

[a] Calculated by linear regression using equation, $k_{rac} = (1/t) \times \ln(ee_o/ee_t)$; all standard errors are 95% confidence level; rate constants in units of 10^{-5} s^{-1}. [b] This value is calculated from temperature dependence of the racemization of **(+)-(*E*,*E*)-1** (Table 3). [c] $\Delta V^{\ddagger}$ is calculated from the linear slope (1−1000 bar) of the correlation of $\ln k_{rac}$ versus p: $\ln k_{rac} = a_1 + b_1 p$; $\Delta V^{\ddagger} = b_1 RT$. [d] $\Delta V^{\ddagger}$ is calculated from all data by means of the quadratic equation, $\ln k_{rac} = a_2 + b_2 p + c_2 p^2$; $\Delta V^{\ddagger} = -b_2 RT$.

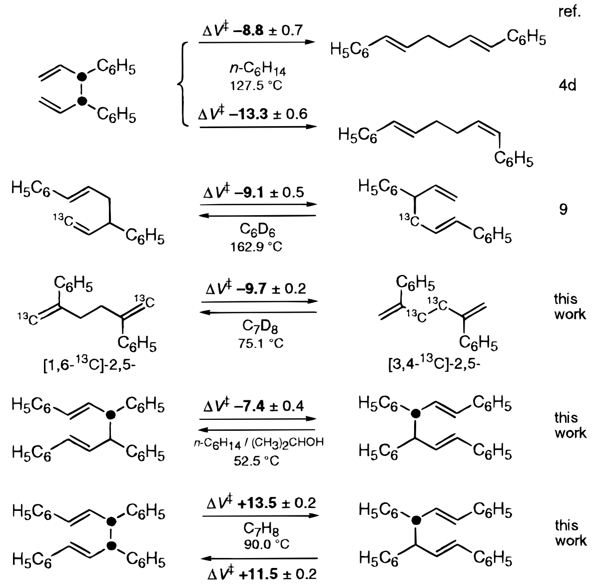

Figure 5. Volumes of activation for hexa-1,5-dienes substituted by phenyl groups in 'active' ('a') positions are shown.

The pairs of (*E*,*Z*)- and (*Z*,*Z*)-isomers have also been examined, but only in a preliminary, pseudo-quantitative manner. For their better study, they have been prepared in enriched form by establishment of photostationary states by triplet-sensitized photoisomerization of ***meso*-(*E*,*E*)-1** and ***rac*-(*E*,*E*)-1** (Table 5). Each of these compounds leads to a mixture of three geometrical isomers from which much of the starting (*E*,*E*)-isomer can be removed by crystallization. Although the residual (*Z*)-isomers have not been isolated in pure form, they are easily characterized with the help of nuclear magnetic resonance (NMR) decoupling. Details are given in the Experimental Section where resonances employed in analysis of their thermal rearrangements are also listed.

The interconversion ***rac*-(*E*,*Z*)-1** ↔ ***meso*-(*E*,*E*)-1** may take place via a chair, *one-axial* transition region (Scheme 1), and is expected to be the next fastest reaction after racemization. By the time the first point is recorded starting with ***meso*-(*E*,*E*)-1** (Table S1, 101 °C, or Table 6, second section, 80 °C), ***rac*-**

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(30) The molar volume calculated for neat ***meso*-** or ***rac*-(*E*,*E*)-1** by the use of Exner increments is given by $V_{calc} = 4 \times V(C_6H_5\text{-(any group)}) + 2 \times V(CH{-}(C_b)) + 4 \times V(CH{=}(C_d)) = 4 \times V(74.04) + 2 \times V(-0.15) + 4 \times (13.47) = 349.74$ cm^3 mol^{-1} (related to 20 °C). This value is in good agreement with the partial molar volumes given in Table SI-5 determined in toluene solution at 20 °C. Because the volume increment, $V(CH{-}(C_d))$, is unknown, we use $V(CH{=}(C_d))$ instead to estimate the molar volume of the (*E*,*E*)-1,3-diphenylallyl radical: $V_{calc} = 2 \times V(C_6H_5\text{-(any group)}) + 2 \times V((CH{=}(C_d)) + 1 \times V((C_d){-}CH{=}(C_d)) = 2 \times (74.04) + 2 \times (13.47) + 1 \times (11.68) = 186.70$ cm^3 mol^{-1}.

(31) Dierkes, G.; Klärner, F.-G.; Rüchardt, C., unpublished results.

(32) For a thorough analysis of the decelerating effect of an axial phenyl group, see Klärner et al.[4d]

Table 5. Photosensitized Irradiation (Benzophenone) of **_rac_-(_E,E_)-1** and **_meso_-(_E,E_)-1** in Benzene-d_6

t, min	**_rac_-(_E,E_)-1**[a]	**_rac_-(_E,Z_)-1**	**_rac_-(_Z,Z_)-1**
0	>99		
30	55.6	34.2	10.2
90	20.9	44.6	34.5
150	15.8[b]	40.0	44.2

t, min	**_meso_-(_E,E_)-1**	**_meso_-(_E,Z_)-1**	**_meso_-(_Z,Z_)-1**
0	>99		
30	77.8	20.2	2.0
90	50.9	40.2	8.9
180	32.2	42.5	25.3
360	13.0[b]	43.6	43.4

[a] Composition in percent. [b] Extraneous signals in the NMR spectrum amount to ∼17% of the total.

Table 6. Thermal Interconversions among the Six Stereoisomeric 1,3,4,6-Tetraphenylhexa-1,5-dienes **1** in Benzene-d_6 at Various Temperatures

t, h	***r*-(*E,E*)**	***r*-(*E,Z*)**	***r*-(*Z,Z*)**	***m*-(*E,E*)**	***m*-(*E,Z*)**	***m*-(*Z,Z*)**
0[a]	100.0[b]	0.0	0.0	0.0	0.0	0.0
24	83.7	0.73	0.0	14.9	0.69	0.0
48	68.0	1.34	0.0	29.1	1.29	0.0
0[a]	0.0	0.0	0.0	100.0	0.0	0.0
24	14.9	7.0	0.0	77.8	0.3	0.0
48	28.0	5.2	0.0	65.3	1.5	0.0
0[c]	0.0	0.0	0.0	0.0	46.0	54.0
13.2	35.1	0.0	0.0	36.3	0.0	28.6
0[d]	13.6	40.7	45.7	0.0	0.0	0.0
7.5	14.0	26.9	45.5	13.6	0.0	0.0
24	17.6	10.5	41.2	30.7	0.0	0.0
42	21.4	5.8	38.9	33.9	0.0	0.0
72	29.7	(*2.9*)[e]	27.5	39.9	0.0	0.0

[a] At 79−80 °C. [b] Relative concentrations in percent. [c] At 110 °C. [d] At 69 °C. [e] This datum missing, an equilibrium concentration is assumed for the purposes of calculation of rate constants.

(_E,Z_)-1 is already in equilibrium ($K = \sim 12$).[33] From the data at 69 °C in Table 6, fourth section, a rate constant, $k_1 = \sim 15 \times 10^{-6}$ s^{-1}, can be estimated. The reaction is ∼30 times slower than a calculated value (69 °C) for the racemization, $k_1 = 430 \times 10^{-6}$ s^{-1}, and ∼30 times faster than the non-Cope interconversion **_rac_-(_E,E_)-1 ↔ _meso_-(_E,E_)-1**.

The Cope rearrangement of **_rac_-(_Z,Z_)-1** to **_rac_-(_E,E_)-1** may occur by way of a chair, *two-axial* transition region (Scheme 1). Again from the data at 69 °C in Table 6, fourth section, an approximate value for the specific rate constant can be calculated ($k_1 = \sim 1 \times 10^{-6}$ s^{-1}), which is quite comparable to that of the non-Cope interconversion ($\sim 0.5 \times 10^{-6}$ s^{-1}).

The interconversion **_meso_-(_E,Z_)-1 ↔ _rac_-(_E,E_)-1** is of the one-axial *boat* type and is ∼8% as fast as the corresponding one-axial *chair* interconversion **_rac_-(_E,Z_)-1 ↔ _meso_-(_E,E_)-1** (data in Table SI-1 and Figure SI-2).

The conversion **_meso_-(_Z,Z_)-1** to **_meso_-(_E,E_)-1**, if a rearrangement of the Cope type at all, may occur as either a three-axial chair or a two-axial boat. The rate constant from the single point at 110 °C in the third section of Table 6 ($k_1 = \sim 13.4 \times 10^{-6}$ s^{-1}) is ∼19% as large as that of the non-Cope interconversion **_rac_-(_E,E_)-1 ↔ _meso_-(_E,E_)-1** (71×10^{-6} s^{-1}; Table 1).

High pressure (9 kbar; 61.8 °C) applied to a 55:17:24:4 mixture of **_rac_-(_E,Z_)-1** and **_meso_-(_E,E_)-1**, and **_rac_-(_Z,Z_)-1** and **_rac_-(_E,E_)-1**, respectively, induces a ∼2-fold increase in the rate of interconversion of the first pair (no change in the second pair being observed), regardless of whether in toluene-d_8 (liquid) or benzene-d_6 (crystalline matrix) (Table SI-5). This evidence points to the rearrangement being of the pericyclic Cope type, as already assumed.

This cursory exploration is an invitation to a more thorough study of the *pure* (*Z*)-isomers as a means of disentangling minimization of axiality from avoidance of the boat conformation. The situation is conceptually similar to that developed in the study of *meso*-3,4-diphenylhexa-1,5-diene.[4] In such an effort, the approximate relative rates of rearrangement to the most stable isomers may be helpful in optimizing kinetic enrichment of the less stable isomers, while optically active materials are potentially available by chiral-column separation or irradiation of optically active **(+)-(_E,E_)-1**.

Discussion

Returning to the rapid racemization of **(+)-(_E,E_)-1**, its $\Delta H^{\ddagger}$ is 12.2 kcal mol^{-1} lower than that of the archetype before correction for conjugative interaction in the educt, or 22.4 kcal mol^{-1} after correction.[34] The implied *extra* stabilization (beyond allylic stabilization) per 1,3-diphenylallyl component is an unusually high −11.2 kcal mol^{-1}. This value is more than double that seen in the cinnamyl component of the rearrangements of 1,4-diphenylhexa-1,5-diene (−4.4 kcal mol^{-1}; see Figure 1)[9] or *rac*-3,4-diphenylhexa-1,5-diene (−4.7 kcal mol^{-1}).[4c] By analogy with the sequence of stabilization energies in allyl, pentadienyl, and heptatrienyl, the reverse might have been expected.[35−37] One explanation for the high energy of stabilization is offered by the theoretical calculations of Hrovat et al.[38] They find an enhancement of −1.9 kcal mol^{-1} beyond additivity in the $\Delta H^{\ddagger}$ of rearrangement for 1,3,4,6-tetracyanohexa-1,5-diene in comparison with 1,3-dicyanohexa-1,5-diene.[39]

Whether the observed $\Delta H^{\ddagger}$ pertains to a single-step, ‘concerted’, ‘aromatic’ transition region or to a two-step process separated by an achiral intermediate closely similar in geometry cannot be decided, for either would suffice to accommodate racemization and its negative $\Delta V^{\ddagger}$. In another hypothetical explanation, a chairlike, achiral “π-complex” between two

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[33] Activation parameters for the rearrangement of the two (*E,Z*)-isomers have been reported by Roth and Hunold[26] based on data (their Table 9) obtained in supercritical carbon dioxide starting with (*E,E*)-isomers, but not the (*E,Z*)-isomers. Calculation of the ratios of the concentrations of **_meso_-(_E,E_)-1** and **_rac_-(_E,Z_)-1** from their data reveals that, for all but the first point at all temperatures, the ratios are equilibrium ratios and have no kinetic value. As a consequence, the calculated activation parameters ascribed to this rearrangement refer to the more slowly interconverting (*E,E*)-isomer.

[34] The archetype is corrected for two increments of stabilization of the educt by phenyl: $33.5 + 2 \times 5.1 = 43.7$ kcal/mol. The effect of the phenyl substitution on the transition region is then $43.7 - 21.3 = 22.4$ or 5.6 kcal mol^{-1} per phenyl group. Had the homolytic−colligative model served as archetypal reference, the effect of the phenyl substitution on the transition region would become $59.8 + 10.2 - 21.3 = 48.7$ or −12.2 kcal mol^{-1} per phenyl group (incredibly high). Also, recall that $\Delta\Delta H = 32.3 \pm 5.8$ kcal mol^{-1}, the difference in enthalpy of formation in solution at ∼250 °C (ESR) between compounds **1** and two (*E,E*)-1,3-diphenylallyl radicals, is too much higher than the enthalpy of activation of racemization credibly to admit the homolytic−colligative mechanism.

[35] Roth, W. R.; Staemmler, V.; Neumann, M.; Schmuck, C. *Liebigs Ann.* **1995**, 1061−1118.

[36] Compare allyl, pentadienyl (extra stabilization, −3.6 kcal mol^{-1}), and heptatrienyl (extra stabilization, −5.9 kcal mol^{-1}).[37] But note the values preferred by Roth et al.: allyl, −14.5 kcal mol^{-1}; cinnamyl, −19.2 kcal mol^{-1} ($\Delta = -4.7$ kcal mol^{-1}); 1,3-diphenylallyl, −26.2 kcal mol^{-1} ($\Delta = -11.7$ kcal mol^{-1}).[35]

[37] Doering, W. v. E.; Sarma, K. *J. Am. Chem. Soc.* **1992**, *114*, 6037−6043.

[38] Hrovat, D. A.; Beno, B. R.; Lange, H.; Yoo, H.-Y.; Houk, K. N.; Borden, W. T. *J. Am. Chem. Soc.* **1999**, *121*, 10529−10537.

[39] Calculated $\Delta\Delta H^{\ddagger}$: −8.5 kcal mol^{-1} and −3.3 kcal mol^{-1}, respectively.

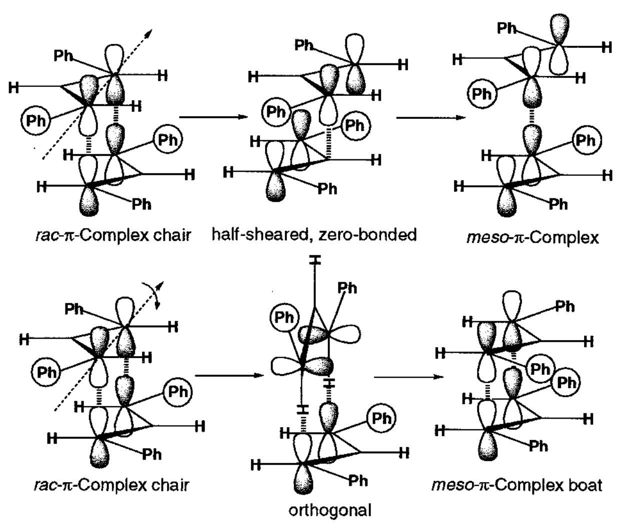

Figure 6. In the upper row, a shearing or sliding pathway for the conversion of ***rac*-(*E*,*E*)-1** to ***meso*-(*E*,*E*)-1** is depicted. In the lower row, a topgraphically distinct conversion of chair to boat conformation leads to the same configurational change.

planar, (*E*,*E*)-1,3-diphenylallyl radicals having weak bonding between two end-on 1/2p-1/2p bonds accounts for the lowering.[40] Roth and Hunold propose van der Waals as the extra force binding the two otherwise noninteracting free radicals.[26]

The non-Cope interconversion of the two (*E*,*E*)-isomers, as we have seen, owes its visibility to a thermodynamic cover provided by the +2.6-kcal mol^{-1} bias that markedly reduces the equilibrium concentrations of kinetically favored Cope involvements of (*Z*)-isomers; and a comfortably accessible rate owing to its large energy of stabilization, which amounts to −57 kcal mol^{-1} vis-à-vis butane (BDE, 87.8 kcal mol^{-1})[41] or −28.9 kcal mol^{-1} vis-à-vis hexa-1,5-diene (BDE, 59.6 kcal mol^{-1}).[12] A pair of kinetically independent, free radicals as intermediary would have provided a simple, attractive rationalization; but trapping, ESR, high pressure, and crossover experiments gave only partial, not full support to a homolytic−colligative mechanism. Failing to find a concerted, energy-lowering pathway to explain intramolecularity, a common fallback invokes a so-called cage phenomenon as a means of preventing kinetic separation by interposing a small barrier to diffusion from the cage. If the conjecture of an achiral Cope-like π-complex (Figure 6) as an intermediate is pursued, severe geometrical readjustments are required to effect interconversion of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1**. One readjustment is a gliding or shearing motion of one half versus the other, through which C-1 ultimately becomes bonded to C-4′. Another readjustment involves a rotation around the cylindrical axis of one of the allylic components that transforms the ***rac*-(*E*,*E*)-1** π-complex into the boatlike π-complex collapsible into ***meso*-(*E*,*E*)-1**. Both transmigrations would appear to pass through a nonbonded region equivalent in energy to two free radicals, but largely, if not completely, would be denied kinetic freedom by the energy of diffusion out of the cage. In the somewhat arcane medium of Roth and Hunold, the radicals had to some extent become free and easily trappable by oxygen. What the third complex might be that Roth and Hunold felt obliged to postulate as an explanation of the slower removal of diene at higher partial pressures of oxygen is not clear, but a solvent-separated pair might be considered, as might the consequences of an ever-increasing concentration of oxygen as a component of the cage.

This study has revealed a phenomenon quite without precedent in the saga of the Cope rearrangement. Its greater significance, however, may lie in the opportunity the system offers to gain a much more intimate view of processes that can occur within a cage than has heretofore been possible.[42]

Experimental Section

General Methods. NMR spectra are recorded on a Bruker AM-500 instrument (^{1}H NMR, 500 MHz; ^{13}C NMR, 126 MHz) in $CDCl_3$ and benzene-d_6, respectively, unless otherwise stated. Chemical shifts are reported in ppm (δ) from tetramethylsilane (TMS) and coupling constants, *J*, in hertz (Hz). Infrared (IR) spectra are recorded on a Perkin-Elmer model 337 grating spectrophotometer and reported in reciprocal centimeters (cm^{-1}). Analytical gas chromatography (GC) is effected on a Hewlett-Packard 5890-A instrument with an HP 3393A recorder-digital integrator using J&W Scientific column (DB 1701: 7% cyanopropyl/7% phenylpolysiloxane), 0.53 mm i.d. × 30 m. Mass spectra are measured on JEOL SX-102 and AX-505 instruments, and the latter is interfaced with a gas chromatograph. Melting points (mp) are uncorrected.

***meso*- and *rac*-(*E*,*E*)-1,3,4,6-Tetraphenylhexa-1,5-diene [*meso*-(*E*,*E*)-1 and *rac*-(*E*,*E*)-1].** These compounds are obtained by two methods: one starting from benzalacetophenone (**A**); another starting from 1,3-diphenylpropene (**B**).

Method A. To a stirred solution of benzalacetophenone (11 g, 0.053 mol, Aldrich) in 110 mL of dry ether cooled to −10 °C under argon, lithium aluminum hydride (0.58 g, 10% molar excess) is added over a 15-min period. After addition of ethyl acetate (2 mL), followed by 5% sulfuric acid (5 mL) and filtration, the ether layer is separated, washed with water, dried over $MgSO_4$, and concentrated in vacuo to a crude product, which is crystallized from heptane to yield 10.1 g (91%) of 1,3-diphenyl-3-hydroxyprop-1-ene: mp 57.5−58.5 °C (lit.[43] mp 57−58 °C); ^{1}H NMR 7.6−7.2 (m, 10H), 6.71 (d, 1H, $J = 15.8$), 6.40 (dd, 1H, $J = 15.8, 6.9$), 5.4 (br s, 1H), 2.1 (br s, 1H).

This alcohol (10 g in 90 mL methanol) is treated with 4 mL of sulfuric acid (*d* 1.84) and left at room temperature overnight. The reaction mixture is poured onto ice and extracted with ether. The ether layer is washed with water, sodium bicarbonate, and water, dried over $MgSO_4$, and concentrated in vacuo to a residue, which is distilled at 0.6 mmHg (bp 120 °C) to give 15 g (78%) of 1,3-diphenyl-3-methoxyprop-1-ene: ^{1}H NMR 7.65−7.18 (m, 10H), 6.75 (d, 1H, $J = 15.9$), 6.43 (ddd, 1H, $J = 15.9, 7.0, 2.0$), 4.92 (d, 1H, $J = 7.0$), 3.49 (s, 3H).

In a slightly modified procedure of Bergmann and Ukai,[15] a solution of 1,3-diphenyl-3-methoxyprop-1-ene (7.5 g; 0.035 mol) in 10 mL of *tert*-butyl methyl ether is added over a period of 10 min to a mechanically stirred suspension of sodium (1.71 g, 2.0 molar equiv) in *tert*-butyl methyl ether (90 mL, freshly distilled from benzophenone ketyl) under argon in a 500-mL Morton flask cooled in an ice bath. After having been warmed to room temperature and stirred overnight, the dark red solution is treated with mercury (190 g), stirred intensively for 26 h, and quenched with solid CO_2. The supernatant liquid is decanted, filtered through Celite, washed with water, dried over $MgSO_4$, and concentrated in vacuo to a colorless, crystalline residue (3.4 g), which is shown by NMR to consist mainly of a mixture of ***meso*-** and ***rac*-(*E*,*E*)-1** (58:42), and some 1,3-diphenylpropene (vide infra). Acidification of the aqueous extract and extraction with ether gives 0.6 g crude α-phenylcinnamic acid: mp 171−172 °C (lit.[44] mp 173 °C) after recrystallization from heptane.

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[40] Professor Weston Thatcher Borden has found that two rigidly planar allyl radicals brought together in the usual chairlike conformation have a bonding distance of ~2.6 Å, and a bonding energy the magnitude of which varies understandably with the level of theory applied in the calculation. We express our gratitude for this calculation and permission to cite.

[41] Seakins, P. W.; Pilling, M. J.; Niiranen, J. T.; Gutman, D.; Krasnaperov, L. N. *J. Phys. Chem.* **1992**, *96*, 9847−9855.

[42] Consider, for example, what compounds such as optically active (*R*,*R*)- or (*R*,*S*)-(*E*,*E*)-1,4-diphenyl-3,6-di-*p*-tolylhexa-1,5-diene have to offer!

[43] Meerwein, H.; Schmidt, R. *Liebigs Ann.* **1928**, *444*, 221−238.

[44] Truett, W. L.; Moulton, W. N. *J. Am. Chem. Soc.* **1951**, *73*, 5913−5915.

Method B. A stirred solution of 7 g of *trans*-1,3-diphenylpropene [obtained according to Raunio and Bonner[45] in 97% of purity (analytical GC) after chromatography on neutral alumina (hexane)] in 180 mL of anhydrous tetrahydrofuran (THF; freshly distilled from benzophenone ketyl) is cooled to −30 °C under nitrogen and treated over a period of 15−20 min with 16.7 mL of 2.5-M *n*-BuLi. The deep-red solution of the anion is stirred at −30 °C for 1.5 h and slowly transferred to a vigorously stirred solution of nitrobenzene (9 g) in anhydrous THF (120 mL) at 0 °C. After a few minutes, the dark brown reaction mixture is quenched with methanol and concentrated in vacuo. Nitrobenzene is removed by distillation at 0.5 mm to give 12.5 g (from 14 g of *trans*-1,3-diphenylpropene) of a residue consisting of equal amounts of ***meso*-** and ***rac*-(*E*,*E*)-1**.

For purification, crude reaction product is dissolved in hexane (1 g per 10 mL) and left overnight at room temperature. The colorless filtrate then consists of two types of crystals, separation of which is achieved by fractional crystallization from methylene chloride−hexane (∼35:65), assisted by manual separation of the more rapidly crystallizing needles from more slowly crystallizing heavy octahedra. From the 12.5 g, for example, four recrystallizations furnished 5 g of the meso isomer (purity >99%), 4 g of the racemic isomer (purity >99%), and 3.5 g of unseparated mixture. Pure ***meso*-(*E*,*E*)-1** (needles) has mp 138 °C: ^{1}H NMR 7.35−6.90 (m, 20H), 6.49−6.39 (m, 2H), 6.30−6.22 (m, 2H), 3.92−3.85 (m, 2H); ^{1}H NMR (300 MHz, toluene-d_8) 7.20−6.80 (m, 20H, H-arom), 6.34 (ddd, 2H, $J_{2,1;5.6} = 15.7$, $J_{2,3;5,4} = 5.0$, $J_{2,4;5,3} = 2.1$, H-2,5), 6.16 (d, 2H, $J_{1.2;6.5} = 15.7$, H-1,6), 3.80 (m, 2H, $J = 5.0$, 2.1, H-3,4); ^{13}C NMR 55.2, 126.1, 126.5, 127.0, 128.3, 128.4, 128.6, 131.1, 131.9, 137.5, 142.4 (11 signals). Pure ***rac*-(*E*,*E*)-1** (octahedra) has mp 143 °C: ^{1}H NMR 7.35−6.90 (m, 20H), 6.65−6.55 (m, 2H), 6.48−6.40 (m, 2H), 3.87−3.80 (m, 2H); ^{1}H NMR (300 MHz, toluene-d_8) 7.20−6.80 (m, 20H, H-arom), 6.53 (ddd, 2H, $J_{2,1;5.6} = 15.7$, $J_{2,3;5,4} = 5.0$, $J_{2,4;5,3} = 2.1$, H-2,5), 6.35 (d, 2H, $J_{1.2;6.5} = 15.7$, H-1,6), 3.78 (m, 2H, $J = 5.0$, 2.1, H-3,4); ^{13}C NMR 55.3, 126.1, 126.2, 127.1, 128.3, 128.4, 128.6, 131.3, 132.2, 137.5, 142.6 (11 signals). The mixture mp of equal parts of ***meso*-** and ***rac*-(*E*,*E*)-1** is 126.6−130.1 °C.

X-ray Crystallographic Structure of *meso*- and *rac*-(*E*,*E*)-1. Details of the structure determinations are found in Supporting Information (Item SI-1 and Figure SI-1).

Kinetics of Thermal Racemization of Optically Active *rac*-(*E*,*E*)-1. The enantiomers of ***rac*-(*E*,*E*)-1** are separated by HPLC on a chiral amylose derivative: CHIRALPAK AD, Mallinckrodt Baker no. 7407-00, 250 × 4.6 mm; flow, 1 mL/min at 22 bar; 70/30 *n*-hexane/2-propanol. The UV detection is at 254 nm (Jasco UV-975). Polarimetric detection is achieved with a Chiralizer IBZ Messtechnik GmbH. Retention times (t_R) of **(−)-(*E*,*E*)-1** and **(+)-(*E*,*E*)-1** are 4.6 and 6.2 min, respectively (see Figure SI-3), were found. Attempts to isolate separate fractions by evaporation of solvents at ∼40 °C in vacuo led to almost entirely racemized samples. For kinetic studies, samples in the solvent are collected directly from HPLC separation, cooled immediately to 0 °C, and used without further attempts at enrichment. Portions of **(+)-(*E*,*E*)-1** in 0.6 mL of 70/30 *n*-hexane/2-propanol are sealed in evacuated glass ampules and heated at the temperatures given in Table 3. During each run, six samples are removed and analyzed by HPLC on the column just described. Specific rate constants, k_{rac}, are calculated as first order, irreversible approach of enantiomeric excess to zero: *ee* = ([**(+)-(*E*,*E*)-1**] − [**(−)-(*E*,*E*)-1**])/([**(+)-(*E*,*E*)-1**] + [**(−)-(*E*,*E*)-1**]).

Procedure for High-Pressure Studies. An autoclave is filled with the pressure-transducing medium (a mixture of 1:1 isooctane/decalin). The reactant is sealed in a poly(tetrafluoroethylene) (PTFE) tube, placed in the autoclave, pressurized to 500 bar, heated to the desired temperature, and then pressurized to the final pressure. The autoclave is a 7-kbar vessel thermostated to ±0.2 °C by an external oil bath, and pressurized by a motor-driven press (Dieckers). One exit of the vessel is connected to a valve equipped with a fine spindle, which allows periodic removal of small samples of ∼600 μL from the 10-mL reactant solution for analysis by HPLC. During the removal, pressure is monitored and maintained by a computer-driven control device. In the high-pressure studies, ^{1}H NMR (300 MHz) spectra are recorded on a Bruker AMX-300 instrument. Analytical gas−liquid chromatography (GLC) is effected on a Hewlett-Packard 5890 instrument with a Shimadzu recorder-digital integrator C-R3A; column C: silicon oil OV 1701 on fused silica (25 m) operated at oven temperature of 70 °C; He. For measurement of densities, a Densimeter DMA 42 (Chempro) is used.

Pressure Dependence of Thermal Racemization of Optically Active (*E*,*E*)-1. Portions of ∼10 mL of a solution of **(−)-(*E*,*E*)-1** in 70/30 *n*-hexane/2-propanol are placed in the 7-kbar vessel as already described and heated to 44.3 ± 0.2 °C at the pressures indicated in Table 4. At each pressure, at least six samples are taken at different times, and their enantiomeric ratios determined by HPLC as already described. A typical result (2.0 kbar) is included in Figure SI-3.

Pressure Dependence of Thermal Rearrangement of 2,5-Diphenylhexa-1,5-diene-1,6-^{13}C (1,6) to 2,5-Diphenylhexa-1,5-diene-3,4-^{13}C (3,4). Solutions of 12 mg of **(1,6)** in 0.8 mL of toluene-d_8 are sealed in PTFE tubes, placed in the 7-kbar vessel, and heated at 75.1 °C for 6 h at the pressures indicated in Table SI-4. Analysis relies on signals at $\delta = 4.9$ and 5.7 of H-1 and H-6 in **(1,6)** coupled to ^{13}C, whereas composite signals of H-1 and H-6 from **(3,4)** and **(1,6)** are found at $\delta = 5.2$ and 5.4. A control experiment confirms that no detectable rearrangement occurs during the heating or cooling period.

Concentration Dependence of the Interconversion of *meso*-(*E*,*E*)-1 and *rac*-(*E*,*E*)-1. Two samples of pure ***meso*-(*E*,*E*)-1** (40 and 4 mg, respectively) in toluene-d_8 (each: 700 μL) are heated at 105 °C for 1.5 and 3.0 h, respectively. The ratio of meso to racemic isomer in the product is determined by the ^{1}H NMR signals (300 MHz) at 6.16 (2H, H-1,6, ***meso*-(*E*,*E*)-1**) and 6.53 (2H, H-2,5, ***rac*-(*E*,*E*)-1**) to be 85.7:14.3 after 1.5 h, 75.5:24.5 after 3.0 h (40-mg sample), 85.7:14.3 after 1.5 h, and 75.9:24.1 after 3.0 h (4-mg sample).

Kinetics of Thermal Rearrangement of *meso*- and *rac*-(*E*,*E*)-1. Kinetic measurements are made generally following the procedure described previously.[35] Samples of **1** are prepared in benzene-d_6 (∼0.028 M) containing 18-crown-6 ether as internal standard (∼0.00213 M) in NMR tubes (no. 528 Pyrex), which are deaerated by three freeze−thaw cycles and sealed in vacuo. Heating is accomplished in the vapor of solvents boiling under reflux: ethyl acetate (77.1−77.6 °C); cyclohexane (80.4−81.0 °C); trichloroethylene (87.1−87.5 °C); dioxane (101.0−101.6 °C); toluene (110.0−110.7 °C); and pyridine (115.0−115.5 °C). Variation in temperature is due to fluctuations in atmospheric pressure, which is monitored periodically.

For analysis, the tubes are removed, cooled, analyzed by NMR, and returned to the vapor bath for further heating and analysis. This process is continued until equilibrium has been established (9−10 half-lives). Quantitative analysis by ^{1}H NMR (500 MHz) is based on signals at 6.65−6.55 from ***rac*-(*E*,*E*)-1** and 6.30−6.22 from ***meso*-(*E*,*E*)-1**. Intensities of the composite signals at 6.65−6.39 and 3.92−3.80 are used for verification, whereas the latter signal is compared with the standard at 3.55 to determine recovery. Accumulation involves 32−64 scans with a 13.04-s interpulse delay, a relaxation delay of 9.77 s, and an acquisition time of 3.27 s. Rate constants are evaluated by the least squares program, NONLIN, based on the equation for reversible first-order reactions: $(x - x_o)/(x_e - x_o) = \exp[-(k_1 + k_{-1})t]$, where x_o, x_e, and x are the mole fractions of the product at time zero, at equilibrium, and at time t, respectively, and k_1 and k_{-1} are rate constants for the conversion of ***rac*-(*E*,*E*)-1** to ***meso*-(*E*,*E*)-1** and the reverse, respectively. In the calculation, x_o, x_e and $(k_1 + k_{-1})$ are varied to achieve least sum of the squares of the deviation in x. In a second approximation, the values of x_e are readjusted to conform to the best fit of the thermodynamic parameters given by a plot of $1/T$ versus log K, the rate constants then being reevaluated. The results are collected in Table 1 along with activation parameters calculated in the usual manner.

Influence of Pressure on the Rate of Interconversion of *meso*-(*E*,*E*)-1 and *rac*-(*E*,*E*)-1. Method A. Two solutions, each of ∼40 mg of pure ***meso*-(*E*,*E*)-1** in 3 mL of anhydrous benzene-d_6 and toluene-d_8, respectively, were prepared. Each solution was divided and introduced into PTFE tubes that had been deactivated by prior treatment with triethylamine. The sealed samples were heated under the conditions given in Table SI-2 and analyzed by ^{1}H NMR as already described. New ^{1}H NMR signals at $\delta = 3.6$, 4.3, and 4.1 assigned to 3-, 4-H of ***meso*-** or ***rac*-(*E*,*Z*)-1** and ***meso*-** or ***rac*-(*Z*,*Z*)-1**, respectively, with a

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[45] Raunio, E. K.; Bonner, W. A. *J. Org. Chem.* **1966**, *31*, 396−399.

maximum intensity of 3% and 1%, respectively, were observed in addition to the signals of ***meso***- and ***rac*-(*E*,*E*)-1**.

Method B. Two solutions of 100 mg each of pure ***meso*-(*E*,*E*)-1** in 6 mL of anhydrous toluene-d_8 and pure ***rac*-(*E*,*E*)-1** in 6 mL of anhydrous toluene-d_8 were prepared. Each solution was divided, sealed in deactivated PTFE tubes, and heated in a thermostated autoclave under the conditions given in Table SI-2. The ratio, ***meso*-(*E*,*E*)-1**-to-***rac*-(*E*,*E*)-1**, of each sample was analyzed by ^{1}H NMR as already described. A control experiment using samples of both solutions showed that, during the period of heating the autoclave from room temperature to 90.0 °C (1.5 h at 1500 bar) and during the period of cooling after the reaction (1.5 h), no isomerization had occurred within the limits of ^{1}H NMR detection. From the product ratios starting either from ***meso*-(*E*,*E*)-1** or ***rac*-(*E*,*E*)-1**, the single-point, first-order specific rate constants (k) in Table SI-2 were obtained by a Marquardt optimization routine.[46] The $\Delta V^{\ddagger}$ values were calculated from the nonlinear correlation, $\ln(k)_p = a + bp + cp^2$, $\Delta V^{\ddagger} = -bRT$ ($R = 83.14$ cm^3 mol^{-1} bar K^{-1}).

ESR Measurements. ESR spectra are recorded on a Bruker ER-420 X-band spectrometer that is equipped with a variable temperature unit and is connected to a PC-based, data acquisition system. Typically, samples are prepared by deaerating of 2×10^{-2} M solutions of ***meso*-(*E*,*E*)-1** in purified diphenyl ether in 4-mm o.d. quartz tubes. Radicals are generated by heating the sealed sample tubes in the cavity of the ESR spectrometer to temperatures in the range 200−300 °C. Further experimental details are found in the Supporting Information (Item SI-2). Hyperfine splitting constants are refined by computer simulation. Radical concentrations are determined by numerical double integration of the digitized, computer-stored spectra and comparison of the integrated ESR signal of a calibrated concentration standard, recorded under the same instrumental settings and taking into account the temperature dependence of the volume of the solution and the temperature dependence of the signal intensity according to the Curie law.

Attempted Initiation by Azobisisobutyronitrile (AIBN). A tube containing a solution of ***meso*-(*E*,*E*)-1** (10 mg) in benzene-d_6 (0.6 mL) and 0.1 g of AIBN is carefully deaerated, sealed under vacuum, and heated at 56.6 °C (refluxing acetone) for 13.5 h. The NMR spectrum of the product is identical to that of the educt. This experiment is repeated at 77 °C for 13.5 h. The NMR spectrum of the product shows the presence of 10% ***rac*-(*E*,*E*)-1**, the same amount obtained on heating ***meso*-(*E*,*E*)-1** under the same conditions in the absence of AIBN.

Effect of Iodine on the Rate of Interconversion of *rac*-(*E*,*E*)-1 and *meso*-(*E*,*E*)-1. Two ~10-mg samples, one of pure ***rac*-(*E*,*E*)-1** and the other containing 3 mg of I_2 in toluene-d_8 (each ~500 μL), were heated at 80 °C for 18 and 38 h, respectively, to give mixtures of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** [without I_2: 88.6:11.4 (18 h) and 78.5:21.5 (38 h); with I_2: 88.1:11.9 (18 h) and 77.4:22.6 (38 h)].

Trapping Experiments. A. Oxygen. A solution of 15 mg of ***meso*-(*E*,*E*)-1** in 1.5 mL of toluene-d_8 containing 1 mg of 18-crown-6 as internal standard is heated under reflux (oil bath) for ~5 h while a slow stream of oxygen is passed through the refluxing solution. The NMR spectrum of the reaction product shows the usual mixture of ***meso***- and ***rac*-(*E*,*E*)-1** in the ratio 54.0:46.0; recovery as determined by the ratio of product to internal standard at $t = 0$ is 1.56 and at $t = 5$ h is 1.58.

B. 2-Methyl-2-nitrosopropane (Nitroso-*tert*-butane). A solution of ***meso*-(*E*,*E*)-1** (19.3 mg, 0.05 mmol, purity >99.6%) and *tert*-BuNO (43.5 mg, 0.5 mmol, 10 equiv) in 1 mL of dry toluene-d_8 is placed in a Pyrex tube, deaerated, sealed under vacuum, and heated at 110.6 °C (toluene vapor) for 13.5 h. The solvent and excess trapping agent are removed under vacuum until a constant weight is achieved. The NMR spectrum of the reaction product (18.5 mg; recovery, 95.9%) shows only ***meso***- and ***rac*-(*E*,*E*)-1** (51:49), and no signals for methyl protons corresponding to an adduct of 1,3-diphenylallyl radical and 2-methyl-2-nitrosopropane.

C. 2,2,6,6-Tetramethylpiperidinyl Oxyl (TEMPO). The reaction just described is repeated exactly with 30 mg of ***meso*-(*E*,*E*)-1** (0.078 mmol) and 85 mg of TEMPO (0.544 mmol, 7 molar equiv) in 3 mL of toluene-d_8. The NMR spectrum gives no indication of the presence of trapped 1,3-diphenylallyl radical.

D. Thermal Rearrangements of *meso*-(*E*,*E*)-1 in Thiophenol. A solution of ***meso*-(*E*,*E*)-1** (89 mg, 0.23 mmol, purity >99%) in freshly distilled thiophenol (6 mL) in a deaerated Pyrex tube sealed under vacuum is heated at 110.6 °C for 13.5 h (10 half-lives). The bulk of the solvent is removed (5 mmHg) to give a residue, an ether (10 mL) solution which is washed with 5% NaOH and water, dried over $MgSO_4$, and concentrated in vacuo. The complicated NMR spectrum of the crude product does not show signals corresponding to ***meso*-(*E*,*E*)-1** or ***rac*-(*E*,*E*)-1**. Flash chromatography on silica gel gives on elution with hexane the following fractions: Diphenyl disulfide: 15 mg; mp 60.3 °C (lit.[47] mp 58−60 °C); m/z: calcd for $C_{12}H_{10}S_2$, 218; found, 218; ^{1}H NMR and Fourier transform (FT) IR spectra identical with those reported in the literature;[48] (*E*)-*1*,3-Diphenylpropene (DPP): 6 mg; calcd for $C_{15}H_{14}$, 194; found, 194; ^{1}H NMR (400 MHz, $CHCl_3$) 7.4−7.0 (m, 10H), 6.37 (d, 1H, $J = 15.8$), 6.30−6.23 (m, 1H), 3.46 (d, 2H, $J = 6.6$) (spectrum identical with lit.[45] at 100 MHz). The purity of both compounds is >99.9%, as determined by GLC [(column temperature 200 °C, He, 4 psi; t_R: 11.9 min, diphenyl disulfide; 8.8 min DPP]. An intermediate fraction (27 mg) consisting of a mixture of diphenyl disulfide and DPP is eluted from the silica gel column. On chromatographing (hexane), this fraction yields an additional 21 mg of DPP, bringing the total to 27 mg.

Further elution with 2% diethyl ether−hexane gives a product (61 mg) corresponding to an addition product(s) of thiophenol to DPP; m/z: calcd for $C_{21}H_{20}S$, 304, found, 304. The ^{1}H NMR spectrum shows a group of aromatic protons at 7.5−6.8 and aliphatic protons as seven distinct groups of multiplets between 2.2 and 3.9 in a ratio 3.06:1, which corresponds to that expected for the “addition product”, 1,3-diphenyl-2-thiophenylpropane. If the calculated amount of DPP in this fraction is 39 mg, the total amount accounted for is 66 mg (74%). The GLC−mass spectroscopy (MS) of this addition product (100% methylpolysiloxane: column DB1, 15 m, He 8 psi, 100−260 °C) shows six (not very well resolved) peaks with similar mass spectra, all containing the molecular ion, m/z 304, but no peak at m/z 486 corresponding to addition of thiophenol to ***meso*-(*E*,*E*)-1**.

Further experiments with thiophenol may be found in Item SI-3.

E. 9,10-Dihydroanthracene. A mixture of ***meso*-(*E*,*E*)-1** (25 mg, 0.06 mmol) and 9,10-dihydroanthracene (353 mg, 1.96 mmol, 32 molar equiv.) in 1 mL of toluene-d_8 is heated at 106−107 °C for 10 h. After separation of most of the 9,10-dihydroanthracene by flash chromatography (hexane), elution with hexane:2% ether affords ***meso***- and ***rac*-(*E*,*E*)-1** (59:41). No anthracene or (*E*)-1,3-diphenylpropene can be detected by GLC analysis.

F. Phenol. A similar experiment using ***meso*-(*E*,*E*)-1** (12.3 mg, 0.03 mmol) and phenol (92 mg, 0.98 mmol) affords ***meso***- and ***rac*-(*E*,*E*)-1** (58:42), but no (*E*)-1,3-diphenylpropene.

Crossover Experiment: Rearrangement of a Mixture of *meso*-(*E*,*E*)-1 and *meso*-(*E*,*E*)-2. (*E*,*E*)-1,3,4,6-Tetra-*p*-tolylhexa-1,5-diene [**(*E*,*E*)-2**] is synthesized by method A used for the preparation of **1**. Experimental details are given in Item S-4. A 1.5% solution of equimolar amounts of ***meso*-(*E*,*E*)-1** (2.5 mg, purity >99.9%) and the less soluble diastereomer, ***meso*-(*E*,*E*)-2** (2.9 mg, purity >99.9%) in toluene-d_8 is divided between two tubes, one of which is deaerated, sealed under vacuum, and heated at 110 °C (toluene vapors) for 13.5 h and the other of which is left unheated as control. Mass spectra of the two samples are recorded by the field desorption method under identical conditions. The unheated sample shows peaks at m/e 386 [**(*E*,*E*)-1**] and 442 [**(*E*,*E*)-2**], whereas the heated sample shows, in addition to peaks at m/e 386 (relative abundance, 13%) and 442 (relative abundance, 14%), a peak at m/z 414 (8%) corresponding to 1,3-diphenyl-4,6-di-*p*-tolylhexa-1,5-diene; m/z: calcd for $C_{32}H_{30}$, 414. The relative intensities of the three peaks (0.93:0.57:1.00) differ from the statistically expected (1.00:2.00:1.00).

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[46] Marquardt, D. W. *J. Soc. Ind. Appl. Math.* **1963**, *11*, 431−441. We thank Dr. R. Fink for a copy of the program KINETIK, which permits optimization by the Marquardt procedure of kinetic schemes with up to seven components.

[47] Stenhouse, J. *Proc. R. Soc. London* **1869**, *17*, 63. Yiannios, C. N.; Karabinos, J. V. *J. Org. Chem.* **1963**, *28*, 3246−3248.

[48] *Aldrich Library of FT IR Spectra*, 1st ed.; Aldrich Chemical Company; vol. 1, p 1183c. *Aldrich Library of NMR Spectra*, 2nd ed.; Aldrich Chemical Company, 1983; vol. 1, p 973D.

Photoisomerization of (*E*,*E*)-1 to (*E*,*Z*)-1 and (*Z*,*Z*)-1. A. With Benzophenone as Sensitizer. Dilute solutions of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1** in benzene-d_6 containing freshly recrystallized benzophenone (5−10 mol %) are irradiated with two 375-watt sun lamps at ∼15 °C. Progress of the reaction is followed by NMR (vide infra). Results are given in Table 5.

B. General Procedure. Dilute (0.5%) solutions of ***rac*-(*E*,*E*)-1** and ***meso*-(*E*,*E*)-1**, freshly recrystallized from hexane, are irradiated in dry benzene containing 5−10% benzophenone under nitrogen at ∼15 °C (water cooling) with two 375-W sun lamps. Irradiation with a high-pressure mercury lamp does not afford isolable products because of extensive polymerization. After removal of benzene in vacuo, the residue is crystallized from hexane at 4 °C overnight to remove most of the recovered (*E*,*E*) educt. The mother liquor is passed through a short silica gel column (elution with hexane) to remove benzophenone. Additional educt is usually removed by concentration and a second crystallization. Four further examples including NMR data are described in detail in Item S-5.

Thermal Rearrangement of a Mixture of *rac*-(*Z*,*Z*)-1 and *rac*-(*E*,*Z*)-1. A dilute solution of a mixture enriched in ***rac*-(*Z*,*Z*)-1** and ***rac*-(*E*,*Z*)-1** in benzene-d_6 is placed in a NMR tube, deaerated, sealed under vacuum, and heated in hexane vapors (69 °C). The progress of the reaction is monitored by NMR. Rate constants calculated from the data in Table 6 for a first-order irreversible reaction ($k_{c,t} = 1.3 \times 10^{-5}$ s^{-1}; $k_{c,c} = 1.9 \times 10^{-6}$ s^{-1}) indicate that the Cope rearrangement of ***rac*-(*Z*,*Z*)-1** occurs seven times slower than that of ***rac*-(*E*,*Z*)-1**.

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Appendix

The orientation of the phenyl groups attached to the central atoms is quite similar in both molecules: the torsion angle is −58.8° in ***meso*-(*E*,*E*)-1** and 62.4° in ***rac*-(*E*,*E*)-1**. In contrast, the orientation of the double bonds relative to the central bond differ significantly, being 121.9° in ***meso*-(*E*,*E*)-1** and 113.2° in ***rac*-(*E*,*E*)-1**. Even more pronounced are the differences in the torsional angles of the phenyl groups attached to the double bonds, being 11.2° in ***meso*-(*E*,*E*)-1** and 23.7° in ***rac*-(*E*,*E*)-1**. This major difference is almost certainly caused by differences in steric congestion. Thus, in ***meso*-(*E*,*E*)-1** and ***rac*-(*E*,*E*)-1**, the double bonds are 1.329(1) (bond lengths in Å units) and 1.313(3), respectively, whereas the single bonds are 1.466(1) and 1.477(3), respectively.

These features in the styrene fragments can be attributed to the better conjugation in the more nearly coplanar arrangement of the double bonds and the phenyl rings in ***meso*-(*E*,*E*)-1**, which would shorten the single bond and lengthen the double bond. Because comparisons within one system are likely to avoid most of the systematic errors and be more significant, we prefer to compare ratios of the lengths of single-to-double bonds. In ***meso*-(*E*,*E*)-1** and ***rac*-(*E*,*E*)-1**, these are 1.1031(13) and 1.1249(33), respectively. To explore the generality of this finding, we correlated this ratio to the torsional angles in 2126 vinyl fragments found in the Cambridge Structural Database.[49] The result is shown in Figure SI-4 and subjected to a linear regression to obtain a rough idea of the dependency. The ratio of the bond lengths, $r(\mathrm{C{-}C})/r(\mathrm{C{=}C})$, is 1.082 for a torsion angle of 0° and 1.140 for 90°. The double bond length is less sensitive than the single bond, which is also shown in a theoretical ab initio study. An energy surface scan for styrene, with the method/basis set combination B3LYP/6-311G(d,p)[50,51] and full geometry optimizations in 10° steps for the vinyl torsion angle, estimated the energy difference at 0° and 90° to be 3.9 kcal mol^{-1}. The dependence of bond length ratio on torsion angle is given in Figure SI-5. At torsion angles of 0° and 90°, the ratios $r(\mathrm{C{-}C})/r(\mathrm{C{=}C})$ are 1.102 and 1.120, respectively.

Supporting Information Available: Various tables, figures, and items as indicated throughout the text are available (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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[49] In the version of CSD, October 1997, with 175 093 entries, compounds were extracted with a vinyl group attached to a carbon atom having two ‘aromatic’ bonds to C, N, O, and S, the primary sp^2-carbon atom of the vinyl group bonded to a hydrogen atom only, and the secondary sp^2-carbon atom left free. Further restrictions included only those structures with an *R* value of <10% and C−C esd values of <0.01 Å. The search was performed with the 3D Search and Research Using the Cambridge Structural Database: Allen, F. H.; Kennard, O. *Chemical Design Automation News* **1993**, *8*, 1831−1837.

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