Diastereomeric Transition States. Relative Energies of the Chair and Boat Reaction Pathways in the Cope Rearrangement[1a]

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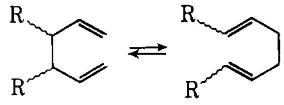
Abstract: Thermal rearrangement of *dl*- and *meso*-2,2′-bismethylenecyclopentane and 2,2′-bismethylenecyclohexane is reported. The rates of rearrangement permit independent measurement of the high- and low-energy conformations of the Cope rearrangement. The transition-state geometry for each diastereomer is uniquely defined as C_{2v} (boat) for the meso isomer and C_{2h} (chair) for the *dl* diastereomer. Correlation of these findings with available data from thermal rearrangement of 1,5-hexadiene establishes that bismethylenecycloalkanes are reasonable models for the isomeric transition states of [3.3] sigmatropic rearrangements. The "characteristic" activation parameters of the Cope rearrangement, in particular the large negative entropy of activation, are consistent with the chair-like (C_{2h}) transition state. The boat-like transition state (C_{2v}), on the other hand, exhibits a slightly positive entropy of activation. Both reactions satisfy mechanistic criteria for concertedness. These results indicate that the entropy of activation does not provide a valid criteria of concertedness. Consideration of stereochemical results from a number of highly substituted derivatives of 1,5-dienes reveals that alternative transition-state geometries C_{2h} (twist) and C_{2v} (plane) are at substantially higher energy than the chair and do not, therefore, play an important role in [3.3] sigmatropic rearrangment of conformationally flexible 1,5-dienes.

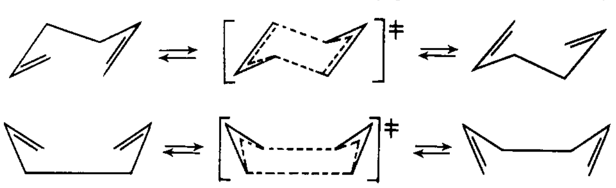
Introduction

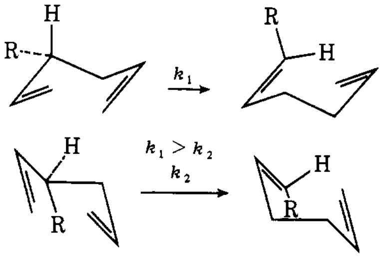
Pericyclic reactions play an increasingly important role in synthetic organic chemistry. One class of reactions that has found widespread application is thermally induced [3.3] sigmatropic rearrangements.[2,3] In the Cope and Claisen modifications of these reactions, bond formation and bond cleavage occur more or less simultaneously.



When substituents are placed on the 1,5-diene, sigmatropic rearrangement can result in the formation of a number of stereoisomeric products. Because of the great synthetic value of this reaction it is extremely important to understand those factors which influence their relative rate of formation.

The basic requirement for reaction involves proximity of the two terminal methylene groups, the site of new bond formation. The resulting cyclic six-atom assembly is free to adopt a variety of conformations. By analogy with the known and carefully investigated conformations of cyclohexane,[4] the chair and boat forms were considered to be two likely possibilities, although a more thorough mechanistic analysis has revealed several alternative transition-state geometries for these rearrangements.[5-7] This added complexity has not altered the impact of the classic investigation of Doering and Roth which established the chair-like transition state as the lowest energy reaction pathway.[8] In an overwhelming majority of cases, the stereochemical outcome of [3.3] sigmatropic rearrangement of substituted derivatives of 1,5-dienes is best understood in terms of a chair-like conformation. Substituents orient themselves so that the bulkiest prefer to occupy the less congested quasi-equatorial positions.[9] This arrangement also usually gives rise to the thermodynamically most stable *E* isomer. Regardless of the origin of this preference, the transition-state model has enjoyed wide success. This success results from the fact that alternative conformations, those that give rise to stereoisomeric products, must lie at substantially higher energy. This occurrence enhances the synthetic utility of the reaction, but at the same time renders independent observation of higher energy conformations quite difficult. As a result of both synthetic and theoretical[10-12] interest in these problems, we have undertaken a study of the relative rates and transition state energy differences between the chair (C_{2h}) and boat (C_{2v}) conformations of the Cope rearrangement.

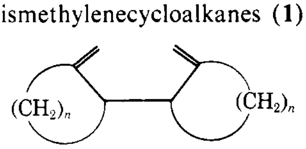




The chemical systems developed in this work provide the opportunity to probe the origin of this preference and will form the basis of a future report.

Results and Discussion

An ideal system for comparison of the chair and boat conformations of a [3.3] sigmatropic rearrangement would consist of an isomeric pair of 1,5-dienes with similar ground-state properties. In addition, the isomers must be constrained in some way so as to undergo rearrangement exclusively by either a chair (local C_{2h}) or boat (C_{2v}) pathway, respectively. A class of molecules that seemed to be promising candidates for this study are the bismethylenecycloalkanes (**1**). The molecule



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possesses the requisite 1,5-diene functionality and will undergo Cope rearrangement to a 1,2-dicycloalkenylethane. This is illustrated for $n = 3$, 2,2′-bismethylenecyclopentane, eq 1. The relationship between these molecules and the conformational variants of the Cope rearrangement is illustrated in Scheme

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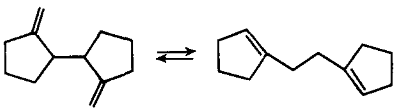


(1)

2 3

I. Bismethylenecycloalkanes exist as a pair of diastereomers, both of which can undergo Cope rearrangement to a common product. The unique aspect of these molecules is the conformation that each diastereomer must adopt in order to undergo rearrangement. In each case the two exocyclic methylene groups must eclipse one another. The meso diastereomer accomplishes this in a six-center or boat-like conformation (local C_{2v} symmetry); other conformations that result from rotation about the 1,1′ bond are, of course, accessible, but the boat-like conformation is the only one from which [3,3] sigmatropic rearrangement can occur. The *dl* diastereomer, on the other hand, gives rise to a quite different geometry; in this case a four-center or chair-like (local C_{2h}) conformation is the only one accessible for Cope rearrangement. This analysis predicts that there should be a large difference in the rates of Cope rearrangement, with the *dl* diastereomer being much more reactive than the meso. Furthermore, rate measurements of the individual diastereomers should yield the rate difference and ultimately the energy difference for the chair and boat transition states of the Cope rearrangement.

The diolefins were prepared by the method outlined in Scheme II. Bis Wittig olefination of either pure or isomeric mixtures of 2,2′-biscycloalkanones give mixtures of bismethylenecycloalkanes. Separation of the diastereomers was accomplished by VPC.

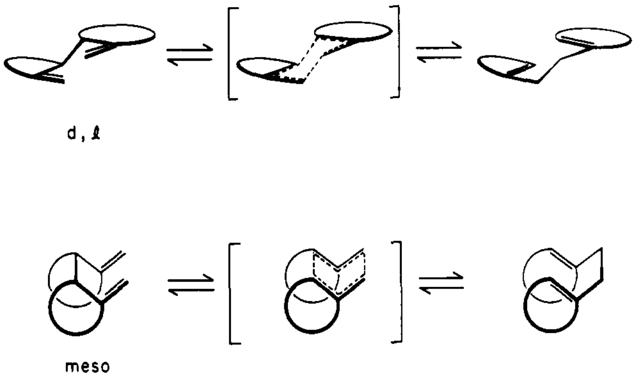
The same diastereomeric ratio of bismethylenecycloalkane (*dl-/meso-***2** 75/25, *dl-/meso-***4** 83/17) is formed regardless of the isomeric diketone used as starting material. This is not surprising since extensive epimerization is known to accompany Wittig olefination.[13] The two diastereomers are estimated to have very similar enthalpies of formation; inspection of molecular models reveals that the *dl* diastereomer may have a slightly higher enthalpy of formation ($\Delta\Delta H° \approx 0.5$ kcal/mol) as a result of cross-ring H-H interactions. The entropy of the racemic modification exceeds that of the meso diastereomer by R ln 2 (1.38 eu). On the basis of the preceding, we assume that the free energies of formation are (within our limits of estimation) the same, $\Delta\Delta G°_{298} = 0 \pm 1$ kcal/mol.

Assignment of stereochemistry of *meso-* and *dl-***4** was achieved by kinetic resolution of the diastereomers using asymmetric hydroboration.[14] An enriched sample of the *d* or *l* isomer, isolated by preparative VPC, showed a rotation $[\alpha]^{23}_{589}$ = −2.88° (hexane). The stereochemical assignment of **2** was based on analogy with that of **4**, namely, chromatographic retention times and chemical reactivity (vide infra).

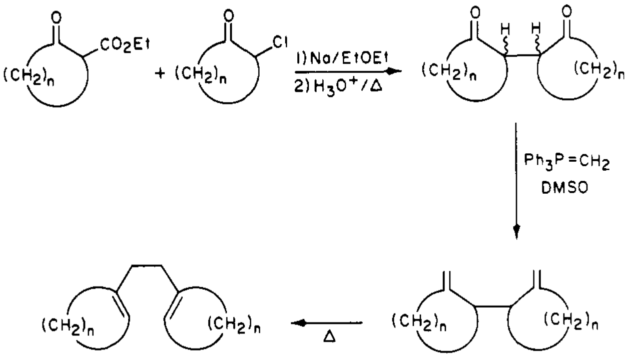
Thermal Rearrangements. When an isomeric mixture of 2,2′-bismethylenecyclopentane (**2**) was heated to 160 °C, the *dl* diastereomer was quantitatively converted to 1,2-dicyclopentenylethane (eq 1, $t_{1/2} \approx 1$ h, $K_{160 °C} > 99.9$). The meso isomer, on the other hand, only begins to react at an appreciable rate when heated to temperatures in excess of 250 °C. A similar pattern of reactivity was found for bismethylenecyclohexane **4**. Rate constants for rearrangement of the individual diastereomers were measured; after extrapolation to an intermediate temperature (200 °C), the rate ratio for the diastereomers of **2** was found to be k_{dl}/k_{meso} (200 °C) = 18 000. These results confirm the basic premise of our conformational analysis of the isomeric bismethylenecycloalkanes.

The rates of Cope rearrangement for **2** and **4** together with several model compounds were examined as a function of temperature to permit evaluation of the activation parameters. These results are included in Table I. Methallylmethylenecycloalkanes (entries 1 and 4) are free to adopt any of a number of conformations for Cope rearrangement. It is interesting therefore to compare their activation parameters with those of the corresponding *dl* diastereomer. Both groups exhibit activation parameters that are characteristic of Cope rearrangements, in particular, large negative entropies of activation in all four examples. It is generally assumed that reactions of similar molecules that have similar activation energies proceed via the same mechanism; a case may be made therefore that these "characteristic" activation parameters are consistent with a low-energy or chair-like conformation of the Cope rearrangement. Hence, methallylmethylenecycloalkanes (entries 1 and 4) undergo rearrangement via the same geometry that is required of the *dl* diastereomers (C_{2h}).

Scheme I



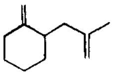
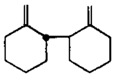
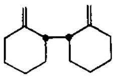
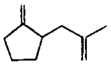
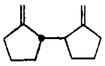
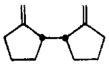
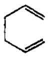
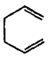
Scheme II



In contrast, comparison of the diastereomeric pairs (entries 2, 3 and 5, 6) reveals striking differences in activation parameters. There are substantial differences in activation enthalpy (13.8-16.1 kcal/mol) and entropy (11.0-13.3 eu); these magnitudes are larger than calculated estimates.[10,11]

Included in Table I are the activation parameters for the low-energy (chair) and high-energy[10] (presumably boat) [3.3] sigmatropic rearrangments of the parent 1,5-hexadiene. The similarity between the meso-*dl* pairs of diastereomers and the parent 1,5-diene should be noted. The data suggest that bismethylenecycloalkanes are reasonable models for the aliphatic 1,5-hexadiene Cope rearrangement. Furthermore, because the transition-state geometry for each diastereomer is uniquely defined as C_{2v} (boat) for the meso isomer and C_{2h} (chair) for the *dl* isomer (Figure 1), similarity of activation parameters argues for similar transition-state conformations in the aliphatic 1,5-hexadiene case. This is important since the isotopically labeled 1,5-hexadienes used to establish the high- and low-energy pathways[10] suffer from ambiguities that do not permit a distinction between the boat (C_{2v}) and plane (C_{2h}) or chair (C_{2h}) and twist (C_{2d}) reaction mechanisms. Thus, it would appear that the characteristic activation parameters for Cope rearrangement, in particular the entropy term, may in certain cases be more narrowly defined so as to

Table I. Activation Parameters for Cope Rearrangement[a]

(entry no.)	compd	$\Delta H^{\ddagger}$	$\Delta S^{\ddagger}_{523}$	$\Delta G^{\ddagger}_{523}$	$\Delta\Delta H^{\ddagger}$	$\Delta\Delta S^{\ddagger}_{523}$	$\Delta\Delta G^{\ddagger}_{523}$
(1)		31.4 ± 0.5	−10.6 ± 1.0	36.9 ± 1.0			
(2)	 *dl*-**4**	29.2 ± 0.5	−8.3 ± 1.2	33.8 ± 1.1	16.1	13.3	9.1
(3)	 *meso*-**4**	45.3 ± 1.0	+5.0 ± 2.0	42.7 ± 1.0			
(4)		30.0 ± 0.3	−13.2 ± 1.0	36.9 ± 0.8			
(5)	 *dl*-**2**	28.0 ± 1.1	−11.4 ± 2.6	33.9 ± 2.4	13.8	11.0	8.1
(6)	 *meso*-**2**	41.8 ± 0.5	−0.4 ± 1.0	42.0 ± 1.0			
(7)	 (low)[b]	33.5 ± 0.5	−13.8 ± 1.0	40.5 ± 1.0	11.2	10.8	5.8
(8)	 (high)[c]	44.7 ± 2.0	−3.0 ± 3.6	46.3 ± 3.8			

[a] Units are in kcal/mol for $\Delta H^{\ddagger}$ and $\Delta G^{\ddagger}$ and cal/(mol·deg) for $\Delta S^{\ddagger}$; subscripts are in K; uncertainties are standard deviations. [b] Reference 15. [c] Reference 16.

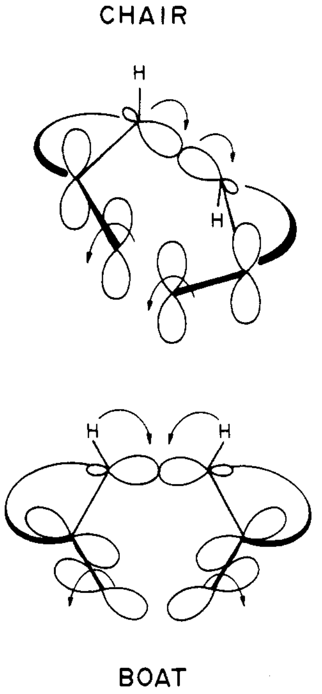


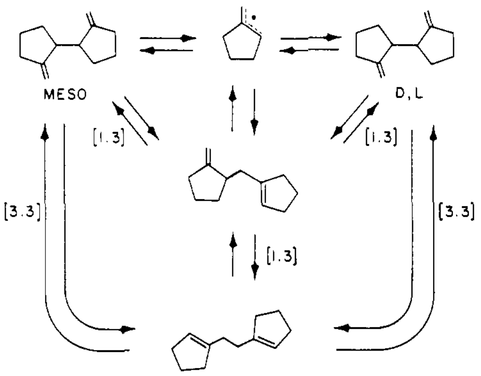
Figure 1.

be representative of the chair-like transition state of [3.3] sigmatropic rearrangements.[17]

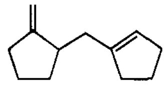
Inspection of molecular models of the meso isomers reveals possible nonbonded interactions between the syn hydrogens of the exocyclic methylenes and the "endo" 4 and 4′ ring hydrogens in the transition state for rearrangement. Interactions of this type can raise the activation energy of the meso isomer relative to the *dl*. It is difficult to estimate the magnitude of these interactions since they will depend, in part, upon the degree of bond formation in the transition state. These nonbonded interactions are expected to be at a minimum in the parent 1,5-hexadiene. To obtain some estimate of their contribution to the free energy of activation of *meso*-**2** and **4**, one can assume that the activation energy parameters for 1,5-hexadiene (entries 7 and 8) are those of a "model" chair and boat transition state. If the entire difference in $\Delta G^{\ddagger}$ between these systems is attributed to nonbonded interactions, a value can be estimated; thus, one calculates 2.3 kcal/mol for *meso*-**2** and 3.3 kcal/mol for *meso*-**4** as the contributions from nonbonded interactions. These values are relatively small considering the complexity of the molecules and tend to further support the validity of bismethylenecycloalkanes, in particular, compound **2**, as good models for the chair and boat conformations of the Cope rearrangement.

Pericyclic reactions, in particular the Cope rearrangement, are frequently characterized by large negative entropies of activation.[18] Although these entropy terms do not always permit valid mechanistic distinctions,[19] the striking differences between the two diastereomers may be interpreted in terms of a change in mechanism. A schematic showing plausible mechanistic alternatives is given in Scheme III. They include dissociation-recombination sequences in addition to formally forbidden sequential [1.3] sigmatropic shifts. Both mechanistic alternatives are found to be unimportant under the reaction conditions. Thermolysis of *meso*-**4** in liquid cumene at temperatures up to 280 °C does not result in formation of detectable quantities of 1-methylcyclohexene or methylenecyclohexene. At temperatures in excess of 285 °C, these two compounds are detected, albeit in small quantities (<2%). If one assumes that these products arise from free radicals produced by homolytic dissociation, from these data one can crudely estimate that the dissociation-recombination pathway is 100 times slower than the concerted boat-like transition state of *meso*-**4** at 285 °C. If our assumption regarding the origin of these products is incorrect, this value represents a lower limit of the dissociation-recombination pathway.

Scheme III



Further support for the concerted nature of these rearrangements obtains from a study of unsymmetrical diene **6**.



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Both dissociation-recombination and [1.3] shift pathways are expected to involve this intermediate. When compound **6** was subjected to the reaction conditions (250 °C, 5.6 h), less than 3% was converted to other products; these products were distinctly different from the Cope product **3**. The failure to detect **6** during both solution-phase and *gas-phase* thermal rearrangement of *meso*-**2** implies that *dl*- and *meso*-**2** react by a [3.3] sigmatropic shift mechanism; both [1.3] sigmatropic rearrangement and homolytic dissociation are higher energy processes.[20] The sizable difference in entropy of activation for the mechanistically similar chair and boat variants of [3.3] sigmatropic rearrangements remains at present a puzzle. Its origin could arise from the intrinsic entropy difference between a chair and boat conformation, estimated in cyclohexane to be 3-6 eu,[21] and/or from an unfavorable secondary orbital interaction present in the boat transition state which could produce a further loosening of the transition-state complex,[22] i.e., **7**. Regardless of its origin, we are provided with an example of a situation where the entropy of activation does not provide a valid mechanistic criterion of concertedness.[23]

7

A more complete stereochemical analysis of orbital symmetry allowed [3.3] sigmatropic rearrangements reveals two variants of the traditional chair and boat conformations.[5-7] These are illustrated schematically in Chart I. The rearrangements are divided into two groups, low energy and high energy, according to the sense of rotation (conrotatory or disrotatory) of the methylene groups. A distinction between each of the forms can be made by considering the manner in which the conrotatory or disrotatory modes are coupled; for example, an out-of-synchronization conrotatory motion of the methylene groups generates a chair (C_{2h}) transition state, Chart I.

Mechanistic distinctions become important from a synthetic standpoint with highly substituted derivatives of 1,5-hexadiene, particularly those systems that involve transfer of asymmetry. This aspect of the Cope and Claisen rearrangements was addressed early in a classic stereochemical investigation by Hill and Gilman.[24] The analysis is presented in Chart II. The labeling pattern in A is capable of distinguishing between chair (plane) and boat (twist) reaction pathways. Experimentally, Cope rearrangement results in formation of a chiral product of extremely high enantiomeric purity. Since racemization must occur via the boat or twist pathways, these data place these transition states at least 3.6 kcal/mol above the chair. The labeling pattern in example B does not permit a distinction between the chair and boat transition states; the stereochemical equivalents are [chair-boat] and [twist-plane]. Experimentally, a high degree of asymmetric induction is also found. Interestingly, racemization involving compounds with this substitution pattern occurs via the twist or plane transition states. The substitution pattern in B is the most frequently encountered in chiral transfer reactions involving Claisen rearrangement; in almost all examples to date, reactions occur with almost perfect transfer of asymmetry.[25] The preceding examples, when taken together, allow us to place the boat, twist, and plane conformations at substantially higher energy than the chair.

Chart I

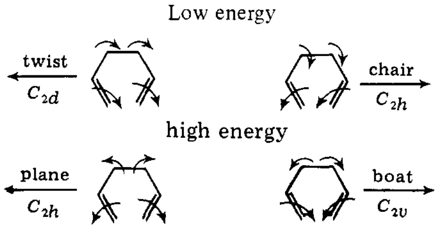
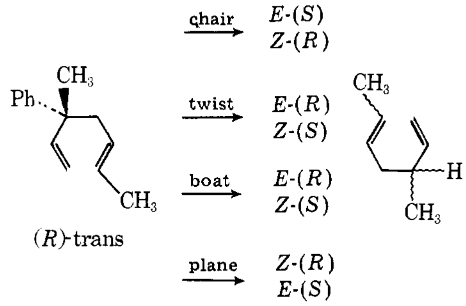


Chart II

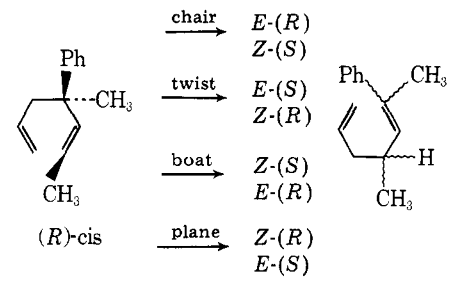
A.



stereochemical equivalents {chair = plane / boat = twist}

experimental result *E*-(*S*) (>94% optical purity)
Z-(*R*) (>96% optical purity)

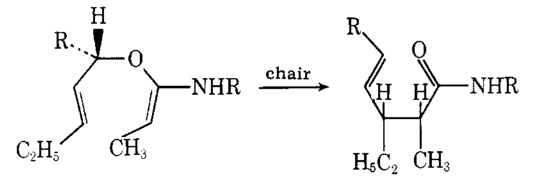
B.



stereochemical equivalents {chair = boat / twist = plane}

experimental results *Z*-(*S*) (>97% optical purity)
E-(*R*) (>99% optical purity)

A complete stereochemical analysis of all four transition-state geometries is available from the results of Sucrow and co-workers.[26] Isomerization of **8** gives *E*-(*R*)(*R*)-**9**, the product expected from the chair transition state. This result



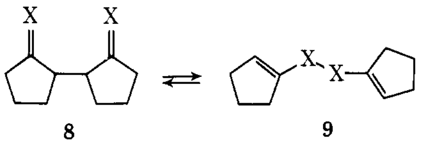
(2)

8 (*E*)-**9**-(*R*)(*R*)

is completely unambiguous in distinguishing the chair transition state from all other “allowed” transition states.

Experimentally there is approximately 10% “leakage” to stereoisomeric products. Uncertainties regarding the origin of the stereochemical leakage prevent a more thorough assignment of relative transition state energies; it is interesting, however, that the racemization pathway to product Z-(S)(S) must occur via the twist mechanism.

Synthetic Applications. The all-carbon rearrangement of bismethylenecycloalkanes is strongly exothermic; hence stereochemical information built in to define the transition-state geometry is lost in the product. In systems that contain suitably placed heteroatoms (X = S, N), eq 3, equilibrium can lie far

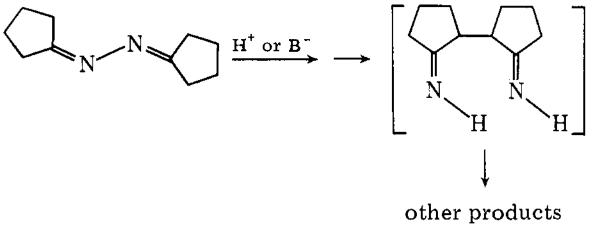


(3)

8 **9**

to the left. By the principle of microscopic reversibility, rearrangement (**9** → **8**) should result in a stereoselective synthesis of the *dl* diastereomer of **8**. This indeed has been realized in the synthesis of 3,3′-dithiapyrrolidones, compounds produced by oxidative coupling of the lithium thioenolate of methylthiopyrrolidone[27] (Scheme IV). Reaction stereospecificity was found to be extremely high; the *dl* diastereomer was the only product isolated in a number of examples.

A similar [3.3] sigmatropic rearrangement has been observed in the acid-[28] and base-catalyzed[29] rearrangement of ketazines (eq 4); the stereochemistry of the kinetically controlled reaction products, however, has not been elucidated.



(4)

Experimental Section

General. Melting points were obtained using a Thomas-Hoover capillary melting point apparatus and are uncorrected. Elemental analyses were performed by Galbraith Laboratories, Inc., Knoxville, Tenn.

Infrared spectra (IR) were recorded on a Perkin-Elmer IR 238 infrared spectrophotometer.

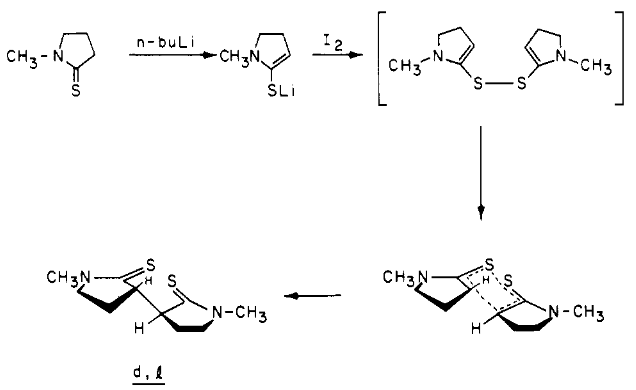
Nuclear magnetic resonance (NMR) spectra were obtained on a Varian Associates A-56/60 spectrometer. Chemical shifts are given in parts per million (ppm) downfield from $(CH_3)_4Si$ in δ units.

For analytical vapor-phase chromatography (VPC), a Hewlett-Packard 5710A gas chromatograph, equipped with flame ionization detector and nitrogen carrier gas, was used. For preparative VPC, a Varian Aerograph Model 920 instrument, equipped with thermal conductivity detector and helium carrier gas, was used.

Most reagent-grade chemicals were dried prior to their use by standard methods available. All organic chemicals were obtained from Aldrich Chemical Co. unless otherwise indicated and the inorganics obtained from Alpha Products Co.

Methylenecycloalkanes. The 1,5-dienes used in this study were prepared by Wittig olefination of the corresponding ketones. Two representative examples follow.

Scheme IV



2-(2-Methyl-2-propenyl)methylenecyclopentane. Freshly distilled 2-(2-methyl-2-propenyl)cyclopentanone (from the pyrrolidine enamine of cyclopentanone and 3-chloro-2-methylpropene, 6.73 g, 0.05 mol) was added to a Me_2SO (25 mL) solution of methylenetriphenylphosphorane[30] (0.06 mol). The resulting mixture was stirred at room temperature for 24 h. The reaction mixture was quenched with saturated ammonium chloride (200 mL) and extracted with ether (thrice), and the combined extract dried (Na_2SO_4). After removal of solvent, the residue was bulb-to-bulb distilled, then fractionally distilled under reduced pressure to yield 3.92 g (57%): bp 77–78 °C (38 mm); IR (neat) 1653 cm^{-1} (alkene); NMR ($CDCl_3$) δ 4.71 (d, 4, olefin), 2.26–1.70 (m, 12, CH_2, CH).

Anal. Calcd for $C_{10}H_{16}$: C, 88.16; H, 11.84. Found: C, 87.97; H, 11.72.

2,2′-Bismethylenecyclohexane (4). To a Me_2SO solution of methylenetriphenylphosphorane (0.08 mol) was added 2,2′-dioxobicyclohexyl[31] (6.04 g, 0.03 mol) in Me_2SO (25 mL). After stirring for 24 h at room temperature the reaction mixture was quenched with saturated ammonium chloride (125 mL), then extracted with ether (thrice). The combined ether extracts were washed with H_2O (200 mL) and saturated sodium chloride (200 mL), then dried (Na_2SO_4). The ether was removed under reduced pressure and the residue distilled to yield 3.21 g (54%): bp 78–80 °C (2 mm); IR (neat) 1644 cm^{-1} (alkene); NMR ($CDCl_3$) δ 4.7–4.6 (m, 4, olefin), 2.5 (m, 2, CH), 2.2–1.5 (m, 16, cyclohexane).

Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.25; H, 11.59.

Compound **4** (*dl* and meso) was separated on 15 ft × 0.19 in. 15% Carbowax 1540 on 60/80 Chromosorb W, 135 °C, 60 mL/min, retention times 10.3 min for *meso* **4**, 12.1 min for *dl*-**4**. The isomers were present in a ratio of 17/83; this same ratio was obtained (±5%) regardless of the isomeric composition of the starting diketone.

2-(2-Methyl-2-propenyl)methylenecyclohexane. In a similar manner 2-(2-methyl-2-propenyl)cyclohexanone[32] (27.9 g, 0.18 mol) and methylenetriphenylphosphorane (0.20 mol) after 1 h gave 11.6 g (44%): bp 105–107 °C (60 mm); IR (neat) 1628 cm^{-1} (alkene); NMR ($CDCl_3$) δ 4.48 (m, 4, olefin), 1.93–1.43 (m, 14, ring hydrogens).

Anal. Calcd for $C_{11}H_{18}$: C, 87.93; H, 12.07. Found: C, 87.32; H, 11.95.

2,2′-Bismethylenecyclopentane (2). Methylenetriphenylphosphorane (0.07 mol) and 2,2′-dioxobicyclopentyl[33] (5.76 g, 0.035 mol) after 36 h at room temperature gave 1.34 g (24%) of diene **2**: bp 84–88 °C (4 mm); IR ($CHCl_3$) 1654 cm^{-1} (alkene); NMR ($CDCl_3$) δ 5.1–4.7 (m, 4, olefin), 2.8–1.7 (m, 14, CH, CH_2).

Anal. Calcd for $C_{12}H_{18}$: C, 88.82; H, 11.18. Found: C, 88.92; H, 11.21.

The *dl*- and *meso*-**2** isomers were separated on a 10 ft × 0.25 in. 30% $AgNO_3$/glycerol column[8] at 65 °C, 60 mL/min, retention times *meso* **2** (38–47 min), *dl*-**2** (62–73 min). The isomers were present in a ratio of 25:75; this same ratio was obtained regardless of the isomeric composition of the starting diketones.

Kinetic Resolution of *dl*-2,2′-Bismethylenecyclohexene. A dry 5-mL flask was charged with $NaBH_4$ (0.042 g, 0.0011 mol), (−)-α-pinene ($[\alpha]^{23}{}_D$ −40.6°, 0.321 g, 0.0024 mol), and 1 mL of dry diglyme.[14] The flask was then equipped with a magnetic stir bar and rubber septum and flushed with nitrogen. After cooling to 0 °C, boron trifluoride etherate (0.180 g, 0.0016 mol) in diglyme (1 mL) was added over a period of 12 min. After 5 h, a thick, white precipitate had formed. A solution of **4** (0.342 g, 0.0018 mol, *dl*/meso = 10) in 0.5 mL of diglyme

Table II. Unimolecular Rate Constants for Cope Rearrangement of Methylenecycloalkanes

compd	temp, °C	K_{obsd} ($\times 10^4$)	compd	temp, °C	K_{obsd} ($\times 10^4$)
2-methyl-2-propenylmethylenecyclohexane	207.0	2.50	*dl*-**2**	168.9	4.73
	191.1	0.83		168.6	4.36
	180.2	0.35		160.4	2.10
	169.4	0.14		159.5	2.10
	160.4	0.10		151.8	1.02
2-methyl-2-propenylmethylenecyclopentane	207.0	2.73		150.3	1.06
	191.1	0.91		143.4	0.58
	180.2	0.40		141.9	0.57
	169.4	0.17	*meso*-**4**	285.3	2.51
	160.4	0.09		278.1	1.60
dl-**4**	168.9	4.86		268.9	0.70
	160.5	2.41		257.7	0.29
	151.8	1.28		249.1	0.14
	142.0	0.51	*meso*-**2**	285.3	4.06
	133.0	0.23		278.1	2.54
				269.1	1.31
				257.5	0.56
				249.1	0.28

was added at once and the mixture stirred for 1 h at 0 °C. A mixture of water (1.5 mL) and hexane (2 mL) was added, and, after separation of the hexane layer, the aqueous phase was extracted twice with hexane. The hexane layers were combined, washed (H_2O), and dried (K_2CO_3). After removal of the hexane the remaining oil was bulb-to-bulb distilled. An enriched sample of the *d* or *l* isomer was isolated by preparative VPC (Carbowax 1540) and exhibited a specific rotation $[\alpha]^{23}_{589}$ −2.88° (hexane). Upon heating the olefin-hexane solution for 170 s at 260 °C, the specific rotation dropped to a negligible value, $[\alpha]^{23}_{589}$ −0.006.

Magnesium Coupling of 2-Bromomethylenecyclohexane. To a stirred, refluxing mixture of magnesium turnings (0.053 g, 0.0022 mol) in dry ether (25 mL) was added a solution of 2-bromomethylenecyclohexane[34] (0.75 g, 0.0043 mol) in ether (10 mL) over 35 min. After addition, the solution was refluxed for an additional 2 h, then quenched with 2% ammonium chloride. The ether layer was separated, washed (H_2O), dried (Na_2SO_4), and concentrated by simple distillation. Bulb-to-bulb distillation gave 0.36 g (85%) of a clear liquid. Gas chromatographic analysis (15 ft × 1/8 in. 8% DC-550 on 80/100 Gas Chrom Q, 150 °C) indicated the following isomeric product distribution: 2,2′-bismethylenecyclohexane (**4**, 9.51%), 1,2-di(1-cyclohexenyl)ethane (**5**, 34.5%), and 2-[methyl-(1-cyclohexenyl)]methylenecyclohexane. The latter product was isolated by preparative VPC: IR ($CDCl_3$) 1642 cm^{-1} (alkene); NMR ($CDCl_3$) δ 5.35 (m, 1, vinyl), 4.5 (m, 2, vinyl), 2.2–1.1 (m, 19).

Anal. Calcd for $C_{14}H_{22}$: C, 88.5; H, 11.65. Found: C, 88.25; H, 11.60.

Magnesium Coupling of 1-Bromomethylcyclopentene. By a procedure identical with that described above 1-bromomethylcyclopentene[35] (4.02 g, 0.025 mol) and magnesium (0.42 g, 0.017 mol) gave 1.83 g (90%) of a mixture consisting of **2** (5.8%), **3** (14.3%), and 2-[methyl-(1-cyclopentenyl)]methylenecyclopentane (**6**, 79.9%). Compound **6** was isolated by preparative VPC (DC-550): IR (neat) 1649 cm^{-1} (alkene); NMR ($CDCl_3$) δ 5.32 (br s, 1), 4.78 (br s, 2), 2.66–1.1 (m, 15).

Anal. Calcd for $C_{12}H_{18}$: C, 88.82; H, 11.18. Found: C, 88.68; H, 11.09.

1-(3-Methyl-3-butenyl)cyclohexane. A neat sample of 2-(2-propenyl)methylenecyclohexene was pyrolyzed in a degassed, sealed Pyrex tube at 192 °C for 24 h. The Cope rearrangement product was isolated by preparative VPC: IR (neat) 1632 cm^{-1} (alkene); NMR (CCl_4) δ 5.58 (m, 1, vinylic), 4.85 (m, 2, vinylic), 2.35–1.98 (m, 15).

1-(3-Methyl-3-butenyl)cyclopentane. A neat sample of 2-(2-methyl-2-propenyl)methylenecyclopentane was pyrolyzed as above for 48 h. The Cope rearrangement product was isolated by preparative VPC: NMR ($CDCl_3$) δ 5.32 (br s, 1, vinyl), 4.68 (br s, 2, vinyl), 2.18–1.74 (m, 13).

Anal. Calcd for $C_{10}H_{16}$: C, 88.16; H, 11.84. Found: C, 88.28; H, 11.83.

1,2-Di(1-cyclopentenyl)ethane (3). A VPC-purified sample of 2,2′-bismethylenecyclopentane in a degassed, sealed pyrolysis tube was heated in a sand bath at 350 °C for 1 h. VPC analysis showed >99% conversion of starting material to the expected Cope product (**3**). The product was isolated by preparative VPC: IR (neat) 1720 cm^{-1} (alkene); NMR ($CDCl_3$) δ 5.33 (m, 1, vinylic), 2.23 (m, 8).

Anal. Calcd for $C_{12}H_{20}$: C, 88.82; H, 11.18. Found: C, 88.91; H, 11.16.

1,2-Di(1-cyclohexenyl)ethane (5). In a pyrolysis identical with the above 2,2′-bismethylenecyclohexane after 1 h at 300 °C gave >99% compound **5**. The product was isolated by preparative VPC: IR (neat) 1668, 912, 727 cm^{-1} (vinylic); NMR ($CDCl_3$) δ 5.37 (br s, 2), 2.33–1.0 (m, 20).

Anal. Calcd for $C_{14}H_{22}$: C, 88.35; H, 11.65. Found: C, 88.30; H, 11.75.

Thermal Reactions. Apparatus. The pyrolyses carried out between 130 and 150 °C were performed in a constant-temperature mineral oil bath contained in a well-insulated 8-L glass battery jar. The bath was constantly stirred and the temperature was measured over a period of 2 h with an accuracy of ±0.2 °C of the reported temperature. The temperature of this bath was measured using National Bureau of Standards calibrated thermometers with 0.1 °C divisions.

The pyrolyses carried out at temperatures above 160 °C were done in a constant-temperature refluxing solvent bath. This bath consisted of a large-neck 1-L round-bottom flask mounted in a heating mantel. The bath was equipped with either a water or air condenser. The round-bottom flask was insulated by wrapping with asbestos cloth and fiberglass. The temperature gradient in the working region of this bath did not vary more than ±0.2 °C. Fluctuations at any one point over a 3-h period were not greater than ±0.2 °C.

Kinetics. The ampule technique was employed. Each tube (80 × 6 mm (i.d.)) was filled via syringe with 5 μL of VPC-purified methylenecycloalkane. The tubes were then degassed three times and sealed on the vacuum at approximately 10^{-3} Torr. Upon removal from the temperature bath, the tubes were immersed in liquid nitrogen, opened, and filled with 50 μL of hexanes. The hexane mixture was then analyzed by VPC. Rate constants are given in Table II. The rate constant at each temperature was determined from the measured ratio of starting material to product as a function of time. The reactions were studied over a range of 3–65% conversion. At least five data points at each temperature were used in the calculation of each rate constant; each data point was the average of the ratios obtained from at least three separate injections. The columns used for the kinetic analysis and the retention time of the reactants are as follows: 8 ft × 1/8 in. 8% Carbowax 1500 (115 °C), *dl*-**2** 8.5 min, *meso*-**2** 8.2 min, 1,2-di(1-cyclopentenyl)ethane 10.5 min; (140 °C) *dl*-**4** 12.1 min, *meso*-**4** 10.3 min, 1,2-di(1-cyclohexenyl)ethane 19.4 min; 10 ft × 1/8 in. 15% Carbowax 20M (90 °C) 2-(2-methyl-2-propenyl)methylenecyclohexane 21 min, Cope product 29.2 min; 2-(2-methyl-2-propenyl)methylenecyclopentane 13 min, Cope product 16.0 min.

Control Reactions. To establish if [1,3] sigmatropic or dissociation-recombination reactions were occurring, decane solutions of **6**, and the six-membered-ring analogue 2-[methyl-(1-cyclohexenyl)]methylenecyclohexane were pyrolyzed for up to 5 half-lives. Cope products, **3** and **5**, were not detected; usually 95–98% of the starting material was recovered. The only products obtained from this reaction were two unknowns, A and B. These products had distinctly different VPC retention times from those of Cope products. Pyrolysis of *meso*-**2** and *meso*-**4**, in both solution phase (decane) and gas phase, produced no detectable quantities of **6** or its homologue. Pyrolysis of *meso*-**4** in liquid cumene at temperatures <280 °C gave no detectable quantities of methylenecyclohexane or methylcyclohexane. At temperatures in excess of 280 °C for contact times >1.25 half-lives, peaks corresponding to the retention times of methylenecyclohexane and 1-methylcyclohexene were detected (<2%). Assuming that radical scavenging is completely efficient and product assignments are correct, a conservative estimate (single point) for the dissociation of *meso*-**4** to two allyl radicals $k_{\text{obsd}}^{285} = 2.5 \times 10^{-6}\ \text{s}^{-1}$.

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References and Notes

(1) (a) This work appeared in a preliminary report: K. J. Shea and R. B. Phillips, *J. Am. Chem. Soc.*, **100**, 654, 2936 (1978). (b) University of California Undergraduate Research Fellow.

(2) Recent reviews include: (a) S. J. Rhoads and N. R. Paulino, *Org. React.*, **22**, 1 (1975); (b) F. E. Ziegler, *Acc. Chem. Res.*, **10**, 227 (1977); (c) A. Jefferson and F. Scheinmann, *Q. Rev., Chem. Soc.*, **22**, 391 (1968); (d) E. N. Marvell and W. Whalley in "Chemistry of the Hydroxyl Group", Vol. 2, S. Patai, Ed., Interscience, New York, 1971, Chapter 13; (e) J. B. Hendrickson, *Angew. Chem., Int. Ed. Engl.*, **13**, 47 (1974).

(3) (a) G. B. Bennett, *Synthesis*, 589 (1977); (b) J. K. Rasmussen, *ibid.*, 91 (1977); (c) B. S. Thyagarajan, *Adv. Heterocycl.*, **8** (1967); (d) E. Winterfeldt, *Fortschr. Chem. Forsch.*, **16**, 75 (1970).

(4) E. L. Eliel, "Stereochemistry of Carbon Compounds", McGraw-Hill, New York, 1962.

(5) M. J. Goldstein and M. S. Benzon, *J. Am. Chem. Soc.*, **94**, 7149 (1972).

(6) J. Gajewski in "Mechanism of Molecular Migrations", Vol. 4, B. S. Thyagarajan, Ed., Wiley-Interscience, New York, 1971, p 1.

(7) H. J. Hansen and H. Schmid, *Tetrahedron*, **30**, 1959 (1974).

(8) W. von E. Doering and W. R. Roth, *Tetrahedron*, **18**, 67 (1962).

(9) C. L. Perrin and J. Faulkner, *Tetrahedron Lett.*, 2783 (1969).

(10) M. J. S. Dewar, G. P. Ford, M. L. McKee, H. S. Rzepa, and L. E. Wade, *J. Am. Chem. Soc.*, **99**, 5069 (1977).

(11) A. Komornicki and J. W. McIver, Jr., *J. Am. Chem. Soc.*, **98**, 4553 (1976).

(12) (a) K. Kukui and H. Fujimoto, *Tetrahedron Lett.*, 251 (1966); (b) M. Simonetta, G. Favini, C. Mariani, and P. Gramaccioni, *J. Am. Chem. Soc.*, **90**, 1280 (1968).

(13) A. Maercker, *Org. React.*, **14**, 270 (1965).

(14) H. C. Brown and G. Zwiefel, *J. Am. Chem. Soc.*, **83**, 486 (1961).

(15) W. von E. Doering, V. G. Toscano, and G. H. Beasley, *Tetrahedron*, **27**, 5299 (1971).

(16) M. J. Goldstein and M. S. Benzon, *J. Am. Chem. Soc.*, **94**, 7174 (1972).

(17) It is doubtful, however, that this observation is a general one. Gajewski and co-workers report the activation parameters for a Cope rearrangement that must proceed via a boat transition state. The activation entropy ($\Delta S^{\ddagger}$ -13.8 ± 2 eu) is very similar to that found for the chair transition state. J. J. Gajewski, L. K. Hoffman, and C. N. Shih, *J. Am. Chem. Soc.*, **96**, 3705 (1974).

(18) R. Willcott, R. L. Cargill, and A. B. Sears, *Prog. Phys. Org. Chem.*, **9**, 25 (1972).

(19) R. E. Lehr and A. P. Marchand in "Pericyclic Reactions", Vol. 1, R. E. Lehr and A. P. Marchand, Eds., Academic Press, New York, 1977, p 2.

(20) Dissociation–recombination pathways are expected to have activation energies in excess of 50 kcal/mol for formation of primary alkylic radicals. See, for example, (a) M. J. Goldstein and M. R. DeCamp, *J. Am. Chem. Soc.*, **96**, 7356 (1974); (b) M. Rossi, K. D. King, and D. M. Golden, *ibid.*, **101**, 1223 (1979), and references cited therein. See also ref 15. Interconversion of meso → *dl* via 1,3-hydrigen migration is an additional possibility. This process should also lead to formation of bis(2-methyl-1-cyclopentene), a stable conjugated isomer of **2**. The failure to detect this isomerization product weakens this mechanistic alternative.

(21) N. L. Allinger and L. A. Freiberg, *J. Am. Chem. Soc.*, **82**, 2393 (1960).

(22) (a) R. Hoffmann and R. B. Woodward, *J. Am. Chem. Soc.*, **87**, 4389 (1965); (b) J. J. Gajewski and N. B. Conrad, *ibid.*, **100**, 6269 (1978).

(23) Concertedness in this instance is rather narrowly constrained and does not include a distinction between a 1,4-cyclohexadiyl diradical and a pericyclic reaction; cf ref 15 and 21 and M. J. S. Dewar and L. E. Wade, *J. Am. Chem. Soc.*, **99**, 4417 (1977); J. J. Gajewski and N. D. Conrad, *ibid.*, **100**, 6268 (1978); R. Wehrli, H. Schmid, D. Bellus, and H-J. Hansen, *Helv. Chim. Acta*, **60**, 1325 (1977); A. Padwa and T. J. Blacklock, *J. Am. Chem. Soc.*, **100**, 1321 (1978).

(24) R. K. Hill and N. W. Gilman, *Chem. Commun.*, 619 (1967).

(25) (a) J. D. Morrison and H. S. Mosher, "Asymmetric Organic Reactions", Prentice-Hall, Englewood Cliffs, N.J., 1971, p 375; (b) D. Valentine, Jr., and J. W. Scott, *Synthesis*, 329 (1978); (c) G. Stork and S. Raucher, *J. Am. Chem. Soc.*, **98**, 1583 (1976); (d) R. J. Cave, B. Lythgoe, D. A. Metcalfe, and I. Waterhouse, *J. Chem. Soc., Perkin Trans. 1*, 2447 (1977); (e) K. Chan, N. Cohen, J. P. DeNoble, A. C. Specian, Jr., and G. Saucy, *J. Org. Chem.*, **41**, 3497 (1976).

(26) (a) W. Sucrow, M. Slopianka, and P. P. Calderia, *Chem. Ber.*, **108**, 1101 (1975), and references cited therein; (b) J. W. Scott and D. Valentine, Jr., *Science*, **184**, 943 (1974).

(27) Y. Tamuru, T. Harada, and Z. Yoshida, *J. Am. Chem. Soc.*, **100**, 1923 (1978).

(28) H. Posvic, R. Dombro, H. Ito, and T. Telinski, *J. Org. Chem.*, **39**, 2575 (1974); we wish to thank Professor Posvic for calling this reaction to our attention.

(29) (a) Z. Yoshida, T. Harada, and Y. Tamura, *Tetrahedron Lett.*, 3823 (1976); (b) Y. Tamaru, T. Harada, and Z. Yoshida, *J. Org. Chem.*, **43**, 3370 (1978).

(30) R. Greenwald, M. Chaykovsky, and E. J. Corey, *J. Org. Chem.*, **28**, 1138 (1963).

(31) S. Glenn and P. Plant, *J. Chem. Soc.*, 1593 (1930).

(32) S. E. Canton and D. S. Tarbell, *J. Am. Chem. Soc.*, **86**, 2903 (1964).

(33) H. Paul, *Chem. Ber.*, **93**, 2395 (1960).

(34) M. Mousseron, R. Jacquier, and A. Fontaine, *Bull. Soc. Chim. Fr.*, 1737 (1956).

(35) P. R. Pal, C. G. Skinner, R. L. Dennis, and W. Shive, *J. Am. Chem. Soc.*, **78**, 5116 (1956).