The Application of the Woodward–Hoffmann Orbital Symmetry Rules to Concerted Organic Reactions

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Introduction

Among the many and varied reactions of olefins certain processes may be properly classified as concerted reactions. The importance of these reactions in organic synthesis is beyond doubt for included within the definition 'concerted' are the well-known Diels–Alder and Cope reactions, and the Claisen rearrangement. There are three main categories of concerted reaction: (i) intramolecular electrocyclic reactions, (ii) intermolecular cycloaddition reactions, and (iii) sigmatropic rearrangements.[1,2] The reactions are subject to thermal and/or photochemical control, and usually proceed in a highly stereospecific manner. Despite the synthetic utility of these reactions until recently their mechanisms were not at all well understood. In many cases the rates of the reactions are little affected by the nature, or on the presence or absence, of solvent or catalyst, and intermediate products are rare. Thus, extensive mechanistic studies have furnished comparatively little detailed information. One general feature of the reactions is the characteristic negative entropy of activation. This is indicative of a high degree of atomic order in the transition state of such reactions.

Recently Woodward and Hoffmann,[1,2] Fukui,[3] and Longuet-Higgins and Abrahamson[4] have interpreted these concerted reactions in terms of the symmetry properties of the reactant and product energy levels. The definitive rules developed by Woodward and Hoffmann are of particular interest to the organic chemist for they not only explain the large majority of these reactions known at present, but permit predictions to be made on reactions hitherto not studied.[1,2,5]

This Review is largely devoted to the qualitative aspects of orbital symmetry relationships, and in particular to examining the application of the Woodward–Hoffmann rules to concerted organic reactions. The rules are based on the results of extended Hückel calculations,[6] and mark an important achievement of

[1] R. B. Woodward and R. Hoffmann, *J. Amer. Chem. Soc.*, 1965, **87**, (a) 395; (b) 2046; (c) 4385; (d) 2511; (e) 4389; see also L. Salem, *ibid.*, 1968, **90**, 543, 553.
[2] R. Hoffmann and R. B. Woodward, Accounts of Chemical Research, Amer. Chem. Soc. Publ., 1968, vol. 1, p. 17.
[3] (a) K. Fukui, *Tetrahedron Letters*, 1965, 2009; *Bull. Chem. Soc. Japan*, 1966, **39**, 498; (b) K. Fukui and H. Fujimoto, *Tetrahedron Letters*, 1966, 251; (c) K. Fukui, *ibid.*, 1965, 2427.
[4] H. C. Longuet-Higgins and E. W. Abrahamson, *J. Amer. Chem. Soc.*, 1965, **87**, 2045.
[5] P. Millie, *Bull. Soc. chim. France*, 1966, 4031; E. M. Kosower, "An Introduction to Physical Organic Chemistry", Wiley, New York, 1968; M. Orchin and H. H. Jaffé, "The Importance of Antibonding Orbitals", Houghton Mifflin Co., Boston, U.S.A., 1967; J. J. Volmer and K. L. Servis, *J. Chem. Educ.*, 1968, **45**, 214.
[6] R. Hoffmann, *J. Chem. Phys.*, 1963, **39**, 1397; 1964, **40**, 2480.

molecular orbital theory. The underlying theoretical principles, of course, require a considerable familiarity with the usual computational methods of molecular orbital theory. The elegant approach developed by Longuet-Higgins and Abrahamson,[4] however, only requires a knowledge of the symmetry properties of the reactant and product energy levels and their relative energies. By the application of Group Theory, the reactant and product energy levels can be correlated graphically, and the conditions (*i.e.*, Δ or *hν*) necessary to perform a particular reaction can be deduced from an inspection of the correlation diagram. Thermally allowed reactions, for example, are characterised by a complete correlation of ground-state energy levels in the reactants with the corresponding ground-state energy levels in the products.

Strictly speaking, the correlation diagrams are only applicable to systems possessing some symmetry since the construction of a diagram for an unsymmetrical system (*i.e.*, one without a plane or two-fold axis of symmetry) can lead to a totally erroneous conclusion. The detailed examination of levels throughout a reaction avoids pitfalls of this type,[2] and in the following discussion the Woodward–Hoffmann rules are applied to several reactions where important symmetry properties are absent. The reactions, of course, must be concerted and in photochemical processes particularly it can be difficult to be completely sure that this prerequisite is met. A theoretical treatment applicable to unsymmetrical systems has been described.[7]

The Article is divided into the following sections: (1) Intramolecular electrocyclic reactions, namely, $4n$ π-electron systems and $4n + 2$ π-electron systems; (2) Intramolecular fragmentation reactions; (3) Intermolecular cycloaddition reactions, namely thermally controlled cycloadditions, photochemically controlled cycloadditions, and metal-catalysed cyclo-oligomerisations; (4) Sigmatropic rearrangements, namely those of order [1, *j*] and [*i, j*]; (5) miscellaneous reactions; and (6) conclusions.

1 Intramolecular Electrocyclic Reactions

It is necessary first briefly to consider the possible stereochemical features of intramolecular electrocyclic reactions. The terminology used throughout is that suggested by Woodward and Hoffmann.[1,2]

Consider the cyclisation of a linear fully conjugated olefin containing k π-electrons, and substituted at the terminal carbon atoms by the groups A—D as shown in Figure 1. The acyclic olefin is drawn such that the lobes of the π-orbitals are parallel to the plane of the paper, whereas the carbon chain (assumed planar) is perpendicular to this plane. In order that a new σ-bond may form between the termini, the terminal π-lobes must interact. This can only arise when concerted rotation about the $C(1)$—$C(2)$ and $C(k-1)$—$C(k)$ bonds brings these terminal lobes sufficiently close for orbital overlap to occur. The rotation may occur in two physically distinct senses: (a) conrotatory or (b) disrotatory, giving rise to the products (I) or (II). In certain cases one can dis-

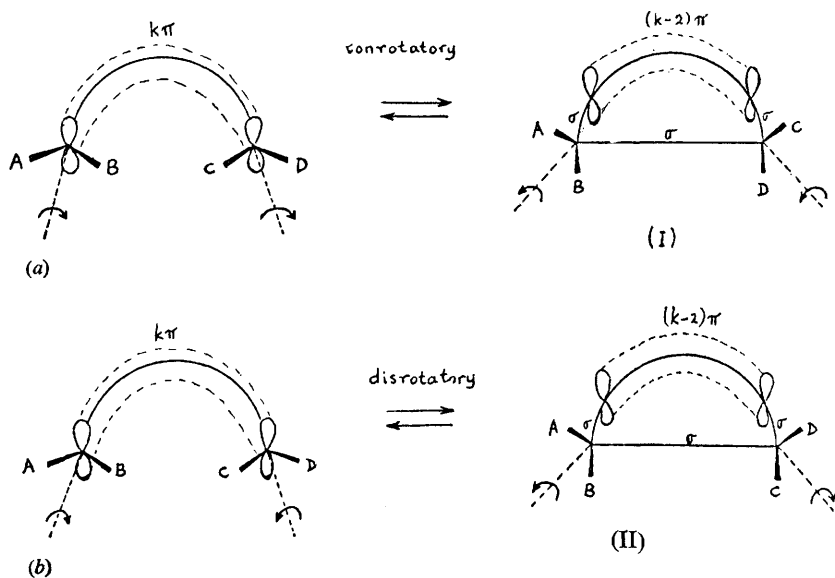[7] H. E. Zimmerman, *J. Amer. Chem. Soc.*, 1966, **88**, 1564, 1566.

Figure 1

tinguish two possible conrotatory or disrotatory modes. Thus in case (b) if the cyclic olefin (II) has $A=D = CH_3$ and $B=C = H$, ring opening could in principle yield a *trans,trans*-1,k-dimethylpolyene or its *cis,cis*-isomer.[1a,2]

In general, these electrocyclic reactions proceed in a highly stereospecific manner under thermal or photochemical control, and the product of the thermal reaction is different from that of the photochemical process. Thus under one form of control path (a) is followed, whereas in the alternative energy pathway the mode (b) applies. In circumstances where there are two possible products, as in the above case (II; $A=D = CH_3$; $B=C = H$), one product usually predominates for reasons of simple steric demand (*i.e.*, the *trans,trans*-1,k-dimethylpolyene should be the major, or only, product).

The stereochemical pathway is predominantly determined by the symmetry properties of the highest occupied molecular orbital (containing two electrons in thermal, ground-state, reactions or one electron in the photochemical, first excited state, processes).[1a,2,4] This bald statement is based upon the results of extensive calculations,[1,2,6] and upon the examination of symmetry state correlation diagrams.[2,4,5,7] An account of these methods cannot be given here, but the basic results can be represented as in Figure 2 which indicates the essential features of orbital symmetry at the termini of $4n$ and $4n + 2$ π-electron systems. The development of a bonding interaction between the termini can only arise if a concerted rotation about the C(1)—C(2) and the C($k - 1$)—C(k) bonds causes an overlap of the terminal lobes such that there is no sign inversion in the region of overlap. The rotations must therefore occur in the physical senses indicated
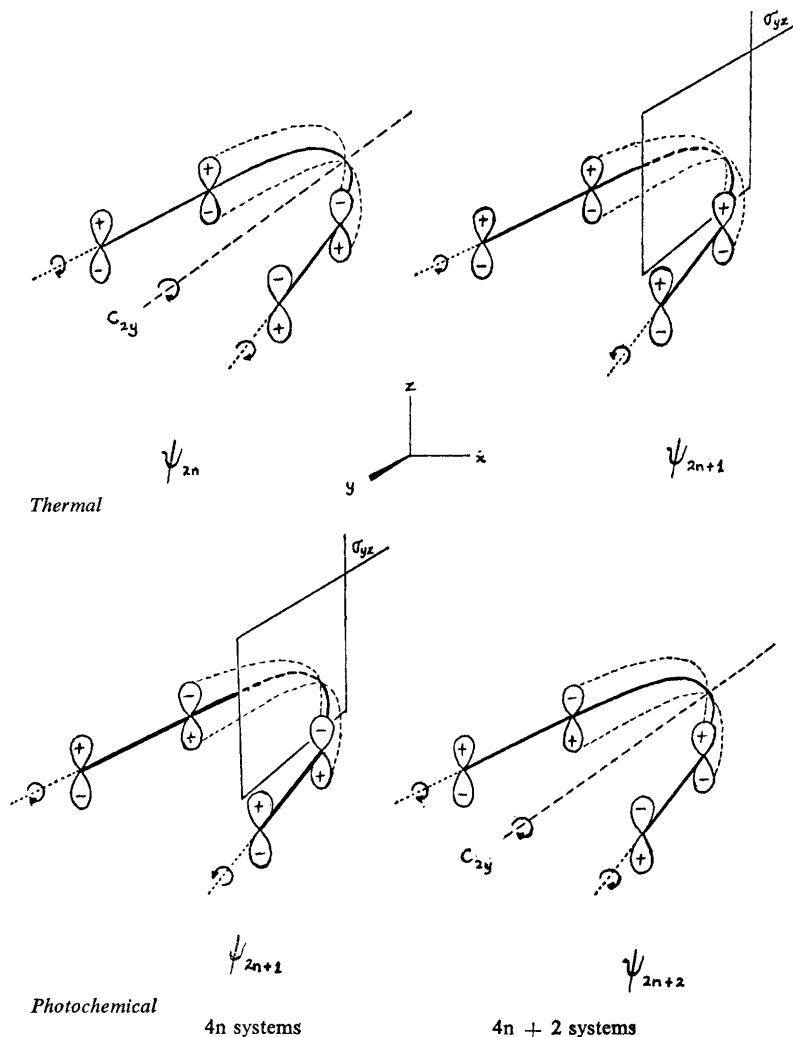
Figure 2 *Orbital symmetries and symmetry elements for the ring closure of* 4n *and* 4n + 2 *π-electron systems. A symmetry axis* (C_{2y}) *is designated for conrotatory ring closure, a symmetry plane* (σ_{yz}) *for disrotatory ring closure.*

in Figure 2. The conrotatory mode is characterised by a two-fold axis of symmetry (C_{2y}) and the disrotatory mode is characterised by a symmetry plane (σ_{yz}). The Woodward–Hoffmann rules for intramolecular electrocyclic reactions may be summarised as in Table 1 according as to whether $\frac{1}{2}k$ is an odd (4n + 2 system) or an even (4n system) integer.[1a,2,4,5] Odd-electron systems (*i.e.*, radicals) behave similarly to even-electron systems possessing one further electron.

Table 1

| k	Thermal	Photochemical
$4n$	*Conrotatory*	*Disrotatory*
$4n + 2$	*Disrotatory*	*Conrotatory*
	$n = 0, 1, 2, 3 \ldots \ldots$	

Charged systems behave similarly to electrically neutral systems containing the same number of π-electrons. The rules are analogous to the spectroscopic selection rules in that they are based on symmetry and are neither a necessary nor sufficient condition for the relevant phenomena to be observed. However, when a particular mode is predicted but cannot operate because of the molecular geometry, the alternative mode may operate under much more highly energetic conditions and a non-concerted mechanism may then apply.

A. $4n$ π-Electron Systems.—(i) *Thermal control (conrotatory mode allowed)*. In this category the most common examples are for the butadiene–cyclobutene interconversion. Many of these examples will not be considered here because the substitution pattern (or lack of it) of the substrate does not allow a distinction to be drawn as to whether a conrotatory process or a disrotatory process has occurred since only one product is possible. Many more examples of the thermal ring fission of cyclobutenes are known than the reverse ring closures which are comparatively rare processes. When the butadiene moiety forms part of a medium-sized alicyclic ring ($\geqslant C_8$), ready thermal cyclisation occurs if the 1,3-diene system has a *cis,trans* geometry. The products (III) and (IV) suffer
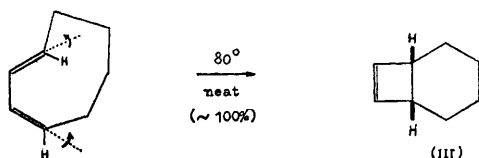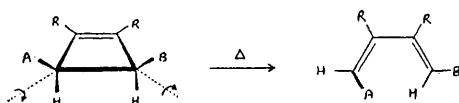

(1)
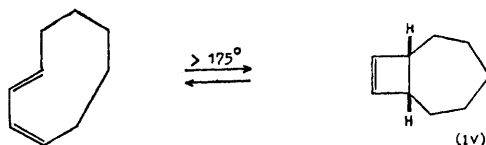
(2)

disrotatory (or non-concerted) ring cleavage to yield the *cis,cis*-monocyclic dienes, but only at considerably higher temperatures.[8] When a *cis,cis*-1,3-diene unit is part of an alicyclic ring ($\geqslant C_9$), conrotatory cyclisation to the *trans*-fused bicyclic systems should be possible [*e.g.*, equation (3)], but examples of this type have not been reported.

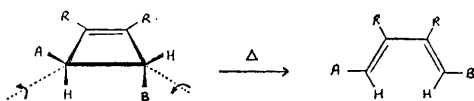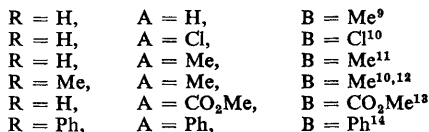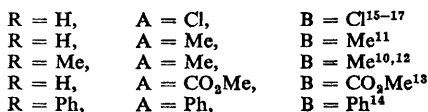[8] K. M. Shumate, P. N. Newman, and G. J. Fonken, *J. Amer. Chem. Soc.*, 1965, **87**, 3996.

$$(n \geqslant 5)$$
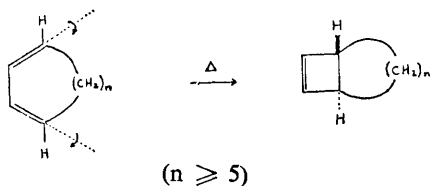
(3)

As mentioned above, the thermal ring cleavage of cyclobutenes is a well-documented process. In the case of simple cyclobutenes[9–17] the essentials can be summarised as in equations (4) and (5). The predicted products are formed in each case. In equation (5) two products are possible in each case: the *trans,trans*-compounds and the *cis,cis*-compounds. The former are produced almost exclusively owing to the lower steric compression in the transition state when the substituents rotate outwards.

(4)

R = H,	A = H,	B = Me[9]
R = H,	A = Cl,	B = Cl[10]
R = H,	A = Me,	B = Me[11]
R = Me,	A = Me,	B = Me[10,12]
R = H,	A = CO$_2$Me,	B = CO$_2$Me[13]
R = Ph,	A = Ph,	B = Ph[14]

(5)

R = H,	A = Cl,	B = Cl[15–17]
R = H,	A = Me,	B = Me[11]
R = Me,	A = Me,	B = Me[10,12]
R = H,	A = CO$_2$Me,	B = CO$_2$Me[13]
R = Ph,	A = Ph,	B = Ph[14]

[9] E. Gil-Av and J. Shabtai, *J. Org. Chem.*, 1964, **29**, 257; H. M. Frey, *Trans. Faraday Soc.*, 1964, **60**, 83.

[10] R. Criegee, D. Seebach, R. E. Winter, B. Borretzen, and H. A. Brune, *Chem. Ber.*, 1965, **98**, 2339.

[11] R. E. K. Winter, *Tetrahedron Letters*, 1965, 1207.

[12] R. Criegee and K. Noll, *Annalen*, 1959, **627**, 1.

[13] E. Vogel, *Angew. Chem.*, 1954, **66**, 640; *Annalen*, 1958, **615**, 14.

[14] H. H. Freedman, G. A. Doorakian, and V. R. Sandel, *J. Amer. Chem. Soc.*, 1965, **87**, 3019.

[15] R. Criegee, W. Hörauf, and W. D. Schellenberg, *Chem. Ber.*, 1953, **86**, 126.

[16] M. Avram, I. Dinulescu, M. Elian, M. Fărcaşiu, E. Marica, G. Mateescu, and C. D. Nenitzescu, *Chem. Ber.*, 1964, **97**, 372.

[17] G. F. Emerson, L. Watts, and R. Pettit, *J. Amer. Chem. Soc.*, 1965, **87**, 131.

Bicyclo[1,1,0]butane (V; $a=b=c=d=H$) is thermolysed to butadiene.[18] In considering the energetics of the process Wiberg and Lavanish[18a] conclude that ring opening occurs by way of a concerted conrotatory path. However, the stereospecificity of the process remains to be demonstrated, for example by utilising (V; $a=c = {}^2H$; $b=d = {}^1H$)[18a] since with (V; $a=c = CO_2Me$; $b=d = H$; $H = Ph$ or $a=d = CO_2Me$; $b=c = H$; $H = Ph$) the results are somewhat confused (the predicted product is not obtained in the former case, but is in the latter process).[18b]

(V)

(6)
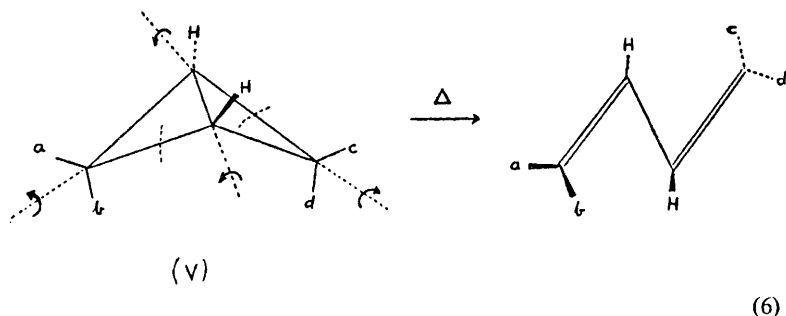
In certain cases the terms conrotatory and disrotatory are meaningless, for example, in the ring cleavages of cyclobuten-3-ones and 3-methylenecyclo-butenes. Nevertheless the processes can be highly stereospecific. This has been demonstrated for the ketone system (VI). Under thermal control the *trans*-products (VII) are obtained, whereas the *cis*-isomers of (VII) are formed in the corresponding photochemical reactions.[19]

(VI)

(VII)

(7)

(a) $R = R' = Cl$
(b) $R = Me$, $R' = Cl$
(c) $R = Cl$, $R' = Me$
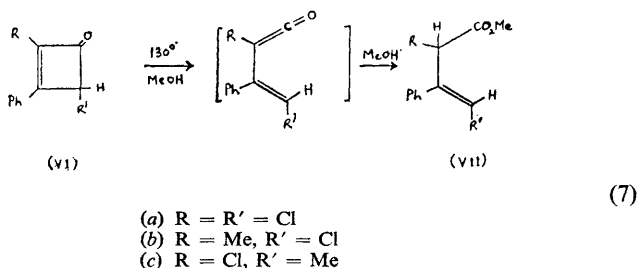
A large amount of work has been carried out on the thermal cleavage of cyclo-butenes in which the cyclobutene moiety forms part of a bicyclic or tricyclic system. Such reactions are expected to be difficult since a *cis,trans*-1,3-diene

[18] (a) K. B. Wiberg and J. M. Lavanish, *J. Amer. Chem. Soc.*, 1966, **88**, 5272; see also K. B. Wiberg and G. Szeimies, *Tetrahedron Letters*, 1968, 1235; (b) I. A. D'yakonov, V. V. Razin, and M. I. Komendantov, *Tetrahedron Letters*, 1966, 1127, 1135.
[19] J. E. Baldwin and M. C. McDaniel, *J. Amer. Chem. Soc.*, 1967, **89**, 1537; see also E. Gil-Av and J. Herling, *Tetrahedron Letters*, 1967, 1.

contained within a ring would be formed in the conrotatory process. However, (VIII) and (IX) ring-open[20] without special difficulty since a *trans*-double bond can be accommodated by the ten-membered rings.

(VIII)

(8)

(IX)
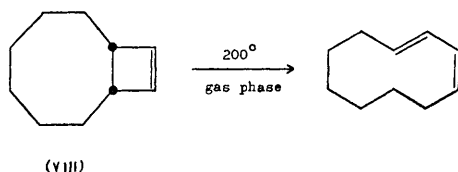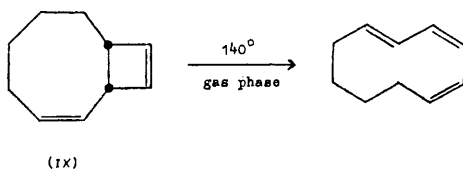
(9)

However, when the second ring of the bicyclic system possesses rather fewer atoms, conrotatory ring fission is clearly impossible. Ring opening must therefore occur by way of the symmetry-forbidden disrotatory mode or by a heterolytic or homolytic pathway, which are predicted to require highly energetic conditions.[1a,2] This conclusion has been substantiated in a number of cases. Thus, for compounds of type (X),[10,11,21–24] in which the two rings are necessarily fused *cis*, ring opening only occurs at high temperatures. A similar situation pertains to the related heterocyclic and carbocyclic systems (XI—XV) which require high temperatures, respectively 350°,[25] 500° (unchanged),[26] 500°,[27] 500° (unchanged),[28] and 360°,[29] for ring opening to occur.

It appears that these difficult ring fissions can be facilitated under mild conditions by the presence of transition-metal ions.[30–32] The mixing of the substrate

[20] P. Radlick and W. Fenical, *Tetrahedron Letters*, 1967, 4901; see also J. J. Bloomfield, *ibid.*, 1968, 587.

[21] (a) M. R. Willcott and E. Goerland, *Tetrahedron Letters*, 1966, 6341; (b) W. G. Dauben and R. L. Cargill, *Tetrahedron*, 1961, **12**, 186.

[22] J. Rigaudy and P. Courtot, *Tetrahedron Letters*, 1961, 95; P. Courtot, *Ann. Chim. (France)*, 1963, **8**, 197.

[23] R. Criegee and H. Furrer, *Chem. Ber.*, 1964, **97**, 2949.

[24] R. Askani, *Chem. Ber.*, 1965, **98**, 2322.

[25] P. R. Story and S. R. Fahrenholtz, *J. Amer. Chem. Soc.*, 1965, **87**, 1623.

[26] R. F. Childs and A. W. Johnson, *J. Chem. Soc. (C)*, 1967, 874.

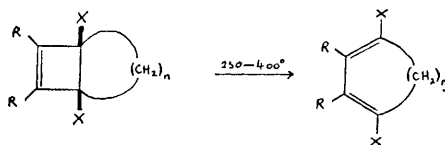[27] E. Vogel, R. Erb, G. Lenz, and A. A. Bothner-By, *Annalen*, 1965, **682**, 1.

[28] G. J. Fonken, *Chem. and Ind.*, 1961, 1575.

[29] M. Jones and S. D. Reich, *J. Amer. Chem. Soc.*, 1967, **89**, 3935.
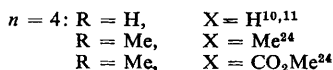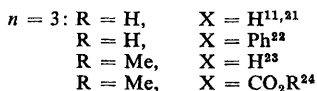
[30] F. R. Mango and J. H. Schachtschneider, *J. Amer. Chem. Soc.*, 1967, **89**, 2484.

[31] (a) H. Hogeveen and H. C. Volger, *J. Amer. Chem. Soc.*, 1967, **89**, 2486; (b) H. Hogeveen and H. C. Volger, *Chem. Comm.*, 1967, 1133.
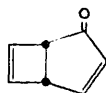
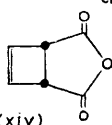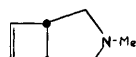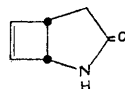[32] W. Merk and R. Pettit, *J. Amer. Chem. Soc.*, 1967, **89**, 4787, 4788.
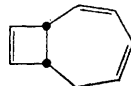
(X)

(10)

$n = 3$: R = H,   X = H[11,21]
      R = H,   X = Ph[22]
      R = Me,   X = H[23]
      R = Me,   X = CO$_2$R[24]

$n = 4$: R = H,   X = H[10,11]
      R = Me,   X = Me[24]
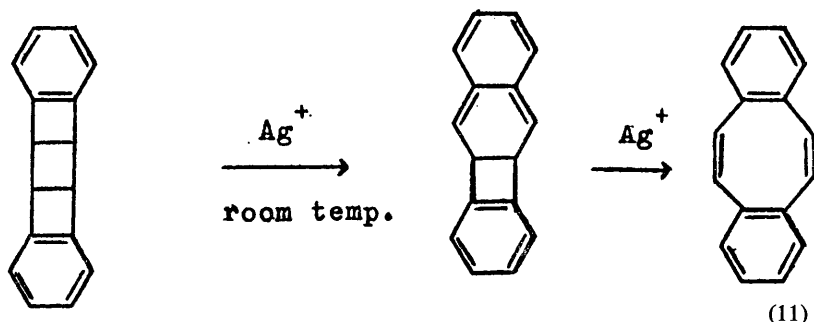   R = Me,   X = CO$_2$Me[24]

(xı)

(xıı)

(xııı)

(xıv)

(xv)

and the metal electronic energy states converts the reaction into a symmetry-allowed process. Thus, a number of tricyclo[4,2,0,0^{2,5}]octa-3,7-dienes are readily isomerised at low temperatures to cyclo-octatetraenes in the presence of silver(ı) and copper(ı) ions.[32] Reaction (11) is typical.
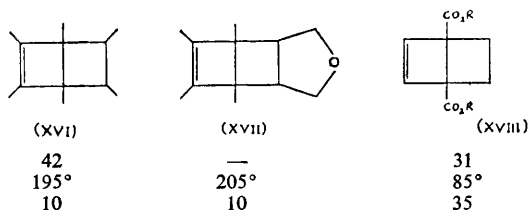

.Ag$^{+.}$
⟶
room temp.

Ag$^+$
⟶

(11)

Nevertheless, there are a number of such isomerisations which occur in the absence of metal catalysts, and at anomalously low temperatures (*i.e.*, low activation energies). Thus bicyclo[2,1,0]pent-2-ene is converted into cyclo-pentadiene at room temperature in carbon tetrachloride solution ($t_{\frac{1}{2}} = ca.$ 2 hr.),[33] and Dewar benzene is isomerised to benzene under similar conditions (room temperature, $t_{\frac{1}{2}} = ca.$ 2 days in pyridine).[34] Both of these bicyclic com-
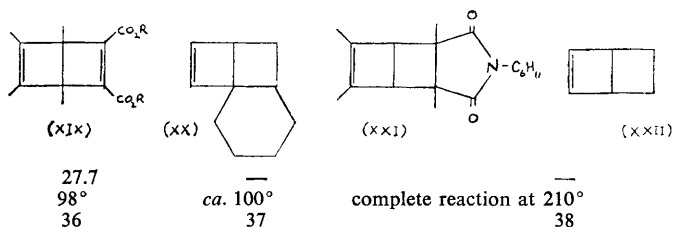
[33] J. I. Brauman, L. E. Ellis, and E. E. van Tamelen, *J. Amer. Chem. Soc.*, 1966, **88**, 846.
[34] E. E. van Tamelen and S. P. Pappas, *J. Amer. Chem. Soc.*, 1963, **85**, 3297; E. E. van Tamelen, *Angew. Chem. Internat. Edn.*, 1965, **4**, 738.

pounds are highly strained, and in the case of Dewar benzene the formation of the low-energy benzene molecule may cause a further lowering of the activation energy for the valence isomerisation. Indeed, it is perhaps surprising that Dewar benzene is so *relatively* stable in view of the large favourable enthalpy change ($\Delta H = -60$ kcal. mole^{-1}) for the isomerisation. In many of the cases in which ring fission of the cyclobutene ring of a bi- or tri-cyclic system occurs at a relatively low temperature, in contravention of the rules, a lowering of the activation energy for the isomerisation may be traced to the release of ring strain in the reactant or to a substantial increase in conjugation in the product. Typical examples of this behaviour are illustrated by the compounds (XVI—XXI).[10,35-38] Activation energy data (where available) and the characteristic reaction temperature (T_{10}^{-4}) at which the rate of cleavage is 10^{-4} sec.$^{-1}$ are included.[10] The data are clearly far from complete, but the introduction of a further ring (XX)

	(XVI)	(XVII)	(XVIII)
$\Delta H\ddagger$(kcal./mole)	42	—	31
T_{10}^{-4}	195°	205°	85°
Ref.	10	10	35

	(XIX)	(XX)	(XXI)	(XXII)
$\Delta H\ddagger$(kcal./mole)	27.7	—		—
T_{10}^{-4}	98°	*ca.* 100°	complete reaction at 210°	
Ref.	36	37	38	

or of a double bond capable of conjugating with the developing 1,3-diene system (XVIII, XIX) has the predictable effect of lowering $\Delta H\ddagger$ and T_{10}^{-4} as compared with (XVI). The activation parameters for (XXII), a more satisfactory reference compound, have apparently not been determined. The easy thermal isomerisation of the azabicycloheptadiene (XXIII) to *N*-ethoxycarbonylazepine[39] (a nonplanar molecule) is more difficult to explain. Further experimentation in this area seems highly desirable.
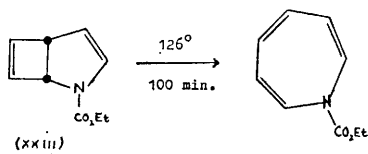
[35] D. Seebach, *Chem. Ber.*, 1964, **97**, 2953.
[36] R. Criegee and F. Zanker, *Angew. Chem. Internat. Edn.*, 1964, **3**, 695.
[37] G. Fonken and U. Mehrotra, *Chem. and Ind.*, 1964, 1025; W. G. Dauben and R. M. Coates, *J. Amer. Chem. Soc.*, 1964, **86**, 2490.
[38] J. B. Bremner and R. N. Warrener, *Chem. Comm.*, 1967, 926.
[39] L. A. Paquette and J. H. Barrett, *J. Amer. Chem. Soc.*, 1966, **88**, 1718; see also L. A. Paquette and R. W. Begland, *ibid.*, p. 4685.

4

$$(12)$$

In the category of $4n$ π-electron systems, reactions other than cyclobutene–butadiene interconversions are relatively uncommon. The conservation of orbital symmetry demands that the concerted cyclisation of the pentadienyl cation to the cyclopentenyl cation should occur by the conrotatory pathway. Such cyclisations have been observed,[40] and the stereoselectivity has now been established in one case. The treatment of 1,1'-dicyclohexenyl ketone with phosphoric acid. yields a mixture of two ketones with the gross structures (XXIV) and (XXV). The stereochemistry of (XXIV), which is diagnostic of the stereospecificity of the cyclisation of the intermediate carbonium ion (XXVI) has been shown to be as indicated by the structure (XXIVa). Hence, the conrotatory cyclisation of (XXVI) is clearly demonstrated.[41]
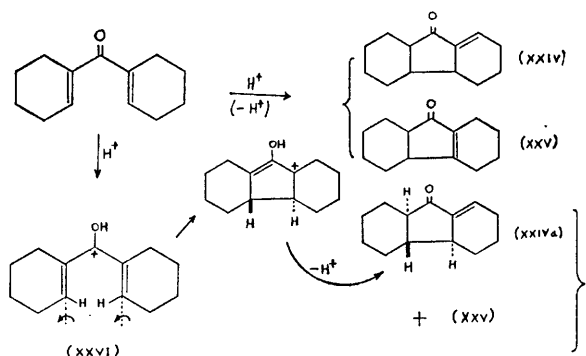

$$(13)$$

The rules further predicted [1a,2] that the thermal isomerisation of the cyclopropyl anion to the allyl anion should follow a concerted conrotatory course. This has now been verified by Huisgen and his co-workers who studied the thermolysis of both *cis-* and *trans-*dimethyl 1-(4-methoxyphenyl)aziridine-2,3-dicarboxylate in the presence of efficient dipolarophiles (*e.g.*, dimethyl acetylenedicarboxylate).[42] The intermediate azomethine ylids (XXVII) and (XXVIII) are thus efficiently intercepted, and the stereospecificity of the initial ring-opening can be deduced from the stereochemistry of the essentially pure adducts (XXIX)

[40] G. A. Olah, C. U. Pittman, and T. S. Sorensen, *J. Amer. Chem. Soc.*, 1966, **88**, 2331; T. S. Sorensen, *ibid.*, 1965, **87**, 5075; *Canad. J. Chem.*, 1965, **43**, 2744; N. C. Deno, C. U. Pittman, and J. O. Turner, *J. Amer. Chem. Soc.*, 1965, **87**, 2153.
[41] R. B. Woodward, in "Aromaticity", *Chem. Soc. Special Publ. No.* 21, 1967, p. 217.
[42] R. Huisgen, W. Scheer, and H. Huber, *J. Amer. Chem. Soc.*, 1967, **89**, 1753.

and (XXX) since dipolar cycloaddition is known to proceed stereospecifically *cis*.

(14)
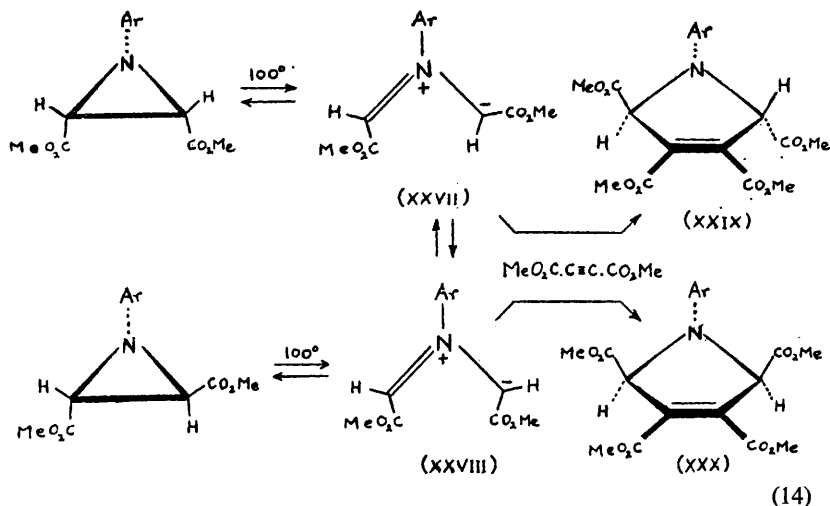
Thermal cyclisations in systems in which $n > 1$ are almost unknown. This is not surprising since in the case $n = 2$ cyclisation would produce an eight-membered ring, and for $n = 3$, a twelve-membered ring. Such processes would be attended by a highly adverse entropy factor as well as a substantially increased activation energy. One possible example of an $n = 2$ system is provided by the hydrogenation of *trans,trans-* and of *cis,trans*-deca-2,8-diene-4,6-diyne over a Lindlar catalyst. In addition to a mixture of over-hydrogenation products, the *trans,trans* compound yields the bicyclic compound (XXXI), whereas (XXXII) is produced from *cis-trans*-deca-2,8-diene-4,6-diyne.[43a] The formation of (XXXI), for example, can be rationalised as in the sequence (15). The conversion (XXXIII)


(15)
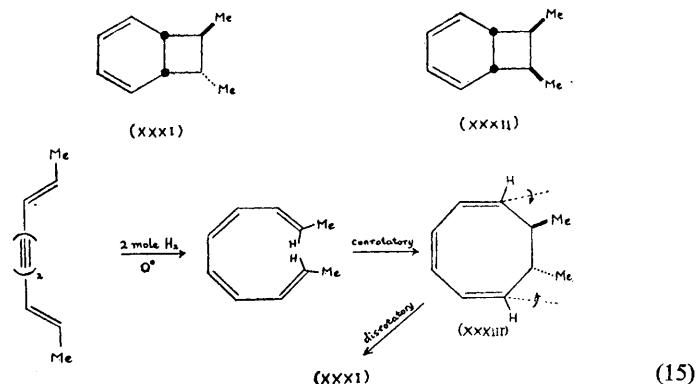
[43] (a) E. N. Marvell and J. Seubert, *J. Amer. Chem. Soc.*, 1967, **89**, 3377; (b) R. Huisgen, A. Dahmen, and H. Huber, *ibid.*, p. 7130 and refs. therein.

$\rightarrow$ (XXXI) is also a thermally allowed process ($4n + 2$ system, disrotation). These conclusions are in agreement with the results of the thermal isomerisation of pure 2,4,6,8-decatetraenes.[43b]

(ii) *Photochemical control (disrotatory mode allowed)*. As in the previous section, the majority of examples are of the butadiene–cyclobutene interconversion.[44] Indeed, the photochemical cyclisations of butadienes is a valuable synthetic route to cyclobutenes. The simple acyclic systems have been extensively studied,[45] but the stereochemistry of the products have not always been defined. The majority of the definitive examples are to be found in systems in which the butadiene chromophore forms part of a ring. Several of these are summarised in reactions (16) and (17).[21,33,39,45–53] The formation of (XXXVc) is surprisingly

(XXXIV) .

$n = 1,$[33] $2,$[46] $3,$[21b,46] $4,$[45a,47,48] and 5[49,50]

(16)

(XXXV)

(17)
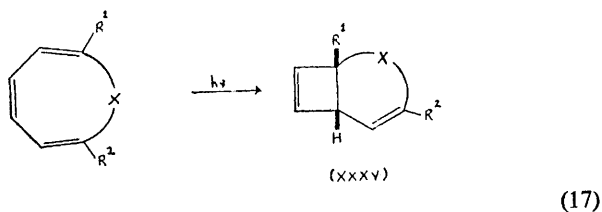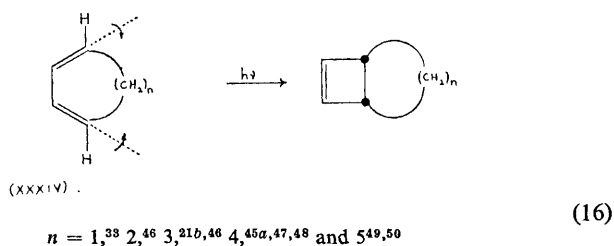
(*a*) R^1, R^2 = H; X = CH_2,[21b,45a] $CH_2.CH_2$,[51] O,[52] NCO_2Et[39]
(*b*) R^1, R^2 = Me; X = O[39]
(*c*) R^1 = OMe; R^2 = H; X = CH_2[53]

specific, and this seems to be a general rule for 1-substituted cycloheptatrienes when the substituent is an electron-releasing group (*e.g.*, R^2 = H; R^1 = Me,

[44] R. Steinmetz, *Fortschr. Chem. Forsch.*, 1967, **7**, 445.
[45] (*a*) R. Srinivasan, *J. Amer. Chem. Soc.*, 1962, **84**, 4141; 1963, **85**, 4045; (*b*) K. J. Crowley, *Tetrahedron*, 1965, **21**, 1001.
[46] H. Prinzbach and E. Druckrey, *Tetrahedron Letters*, 1965, 2959.
[47] R. S. H. Liu, *J. Amer. Chem. Soc.*, 1967, **89**, 112; see also D. I. Schuster, B. R. Sckolnick, and F.-T. H. Lee, *ibid.*, 1968, **90**, 1300.
[48] W. G. Dauben and R. L. Cargill, *J. Org. Chem.*, 1962, **27**, 1910.
[49] K. M. Schumate and G. J. Fonken, *J. Amer. Chem. Soc.*, 1966, **88**, 1073.
[50] K. M. Schumate, P. N. Neuman, and G. J. Fonken, *J. Amer. Chem. Soc.*, 1965, **87**, 3996.
[51] W. R. Roth and B. Peltzer, *Angew. Chem. Internat. Edn.*, 1964, **3**, 440.
[52] J. M. Holovka and P. D. Gardner, *J. Amer. Chem. Soc.*, 1967, **89**, 6390.
[53] G. W. Borden, O. L. Chapman, R. Swindell, and T. Tezuka, *J. Amer. Chem. Soc.*, 1967, **89**, 2979.

OMe, SMe, and NMe$_2$).[54] Similarly the irradiation of homotropylidene[55] and 2,3-homotropone[56] yields only one of the two possible isomers arising from the photochemical disrotatory process in each case. This result has been ascribed to secondary steric forces which raises the activation energy of the alternative disrotatory pathways.[56]

In certain cases it appears that the observed photochemical reaction may in fact comprise two discrete steps. Thus the acetophenone-sensitized irradiation of (XXXIV; $n = 4$)[47] yields the *cis,trans*-isomer of (XXXIV; $n = 4$) which cyclises by the conrotatory mode at 80° to give a bicyclic product identical with that produced in the direct unsensitized reaction of (XXXIV). In connexion with this observation, Liu[47] has suggested that the sensitized photochemical cyclisation of 1,1'-bicyclohexenyl[57] also occurs by way of a two-step reaction (18). The product (XXXVI) is also formed in the direct (unsensitized) reaction
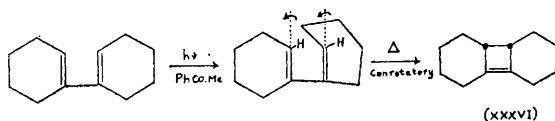
$$(18)$$

by the disrotatory pathway.[57] A *trans*-fused cyclobutene ring may be formed from monocyclic systems possessing a *cis,trans*-1,3-diene unit if the ring is sufficiently large. Thus, irradiation of *cis,cis*-1,3-cyclononadiene (XXXVII) yields both a *cis*- and a *trans*-fused cyclobutene (19). The products are formed by disrotatory cyclisations of (XXXVII) and its *cis,cis*-isomer (XXXVIII), which itself is produced in an initial and rapid photo-equilibrium.[49] Likewise Faren-
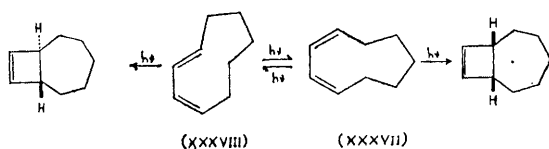
$$(19)$$

horst[58] has suggested that Möbius benzene (*i.e.*, *cis,cis,trans*-cyclohexa-1,3,5-triene) is possibly the intermediate in the photochemical isomerisation of benzene to Dewar benzene. Alternative explanations[2,59] of this process, however, appear more attractive.

An outstanding example of the use of these reactions in preparative organic

[54] A. P. Ter Borg, E. Razenberg, and H. Kloosterziel, *Chem. Comm.*, 1967, 1210.
[55] W. R. Roth and B. Peltzer, *Annalen*, 1965, **685**, 56.
[56] L. A. Paquette and O. Cox, *J. Amer. Chem. Soc.*, 1967, **89**, 5633.
[57] W. G. Dauben, R. L. Cargill, R. M. Coates, and J. Saltiel, *J. Amer. Chem. Soc.*, 1966, **88**, 2742.
[58] E. Farenhorst, *Tetrahedron Letters*, 1966, 6465.
[59] D. Bryce-Smith and H. C. Longuet-Higgins, *Chem. Comm.*, 1966, 593.

chemistry is furnished by the elegant synthesis (20) of Dewar benzene.[34] The irradiation of substituted cyclohexadiene anhydrides yields mainly aromatic hydrocarbons. The latter reaction can be suppressed by using the córresponding imides.[38] The similar reaction of α-pyrone (21)[60] promises to be a useful and
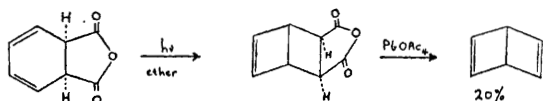

(20)

simple route to cyclobutadiene (isolated as the iron tricarbonyl complex).[61]
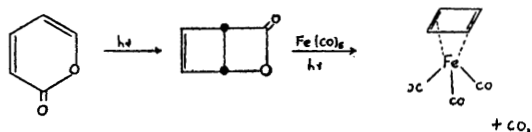
(21)

Cyclopropyl anions have also been shown to follow the predicted disrotatory course. Thus, the irradiation of the *cis*- and *trans*-aziridines discussed earlier (eqn. 14) in the presence of dimethyl acetylenedicarboxylate yields the expected products; *cis*-aziridine ⟶ (XXX), *trans*-aziridine ⟶ (XXIX).[42] The rules are also obeyed for systems in which $n = 2$, although few such reactions are known. Upon irradiation (XXXIX) ring-expands to give [16]-annulene,[62] an example of double disrotation, and (XL) under similar conditions is converted into 9-ethoxycarbonylcyclonona-1,3,5,7-tetraene, which is further transformed under the influence of heat and light.[63]

(xxxix)   (xl)
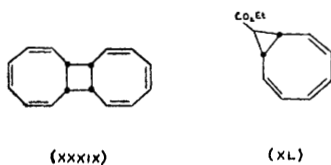
B. $(4n + 2)\pi$-Electron Systems.—(i) *Thermal control* (*disrotatory mode allowed*). The simplest system here is provided by the case $n = 0$ corresponding to the cyclopropyl–allyl cation interconversion. Molecular orbital calculations[1a,2] indicate a very high stereospecificity for the ring-opening if the ionisation of a suitable leaving group (*e.g.*, tosylate or halide) and disrotation are completely

[60] E. J. Corey and J. Streith, *J. Amer. Chem. Soc.*, 1964, **86**, 950.
[61] M. Rosenblum and C. Gatsonis, *J. Amer. Chem. Soc.*, 1967, **89**, 5074.
[62] G. Schröder and J. F. M. Oth, *Tetrahedron Letters*, 1966, 4083.
[63] G. J. Fonken and W. Moran, *Chem. and Ind.*, 1963, 1841.

concerted. The experimental investigations of De Puy and his co-workers have led them independently to the same conclusion.[64] The cyclopropane substituent groups *trans* to the leaving group (X) rotate outwards (or *cis*-substituents rotate inwards) with concerted loss of X^-. In this way the departure of X^- is anchimerically assisted by rear-side orbital overlap.[64] These preferred modes of disrotation are represented in equation (22), and it should be noted that only acyclic allyl

Allylic products

(22)

Allylic products
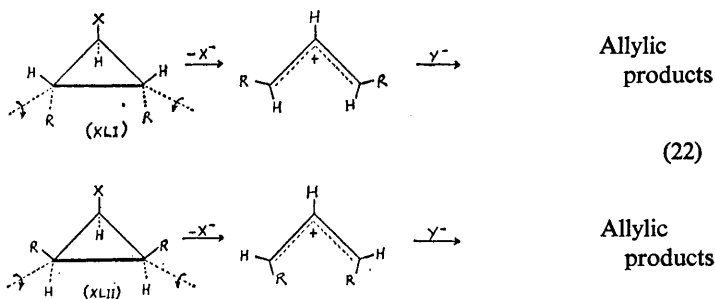
cations are under consideration. The situation is therefore precisely defined: (XLI) should react more quickly than (XLII) in identical experimental conditions since the steric compression of the incoming groups of the *cis*-compound raises the energy of *cisoid* transition state. This conclusion has been amply verified by various solvolysis studies.[64,65]

When ionisation of X and ring-opening are simultaneous, the cyclopropyl cation is not a true intermediate since it does not have a finite lifetime. In a discrete cyclopropyl cation the positively charged carbon atom and the atoms bonded to it presumably adopt a planar configuration. On symmetry grounds alone both of the possible disrotatory modes are identical in these circumstances, and relatively non-specific ring-opening may be found. In this connexion Kirmse and Schütte have shown that both *cis*- and *trans*-2-phenylcyclopropanediazonium ions decompose in methanol to give *trans*-cinnamyl methyl ether.[66] The result is consistent with the intermediacy of the 2-phenylcyclopropyl cation in the reaction.

In the case of the concerted solvolytic cleavage of cyclopropyl tosylates and halides the above ideas can be extended to include bicyclo[n,1,0]alkyl tosylates and halides. The predictions for the bicyclic systems are essentially the reverse of those for the monocyclic compounds.[65] Thus halides and tosylates with the *endo* configuration (XLIII) should react rapidly by the concerted mechanism since the *cis*-allyl cation can be favourably accommodated in a ring structure.

[64] C. H. DePuy, L. G. Schnack, J. W. Hausser, and W. Wiedemann, *J. Amer. Chem. Soc.*, 1965, **87**, 4006; S. J. Cristol, R. M. Sequeira, and C. H. De Puy, *ibid.*, p. 4007; C. H. DePuy, L. G. Schnack, and J. W. Hausser, *ibid.*, 1966, **88**, 3343; J. W. Hausser and N. J. Pinkowski, *ibid.*, 1967, **89**, 6981.
[65] P. von R. Schleyer, G. W. Van Dine, U. Schöllkopf, and J. Paust, *J. Amer. Chem. Soc.*, 1966, **88**, 2868 and refs. therein.
[66] W. Kirmse and H. Schütte, *J. Amer. Chem. Soc.*, 1967, **89**, 1284.

353

The *trans* ring opening required for the *exo*-compound (XLIV) is clearly impossible for small rings, and a more conventional type of transition state might be expected for the *exo*-isomers. In agreement with this generalisation it has

$$(23)$$
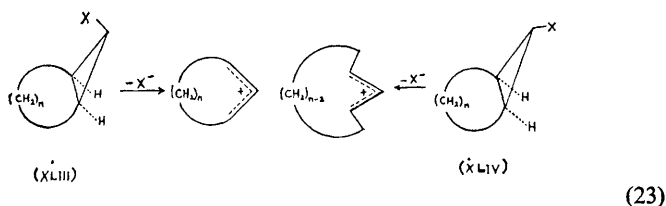
been found that many *endo*-bicyclo[n,1,0]alkyl tosylates and halides react more quickly than the corresponding *exo*-compounds, at least for $n = 2$ or 3.[64,65,67,68] When more bridging atoms are present ($n \geqslant 4$) in the *exo*-compounds (XLIV) the situation becomes more complex. As n increases through 4 to 5 and 6 in (XLIV; X = OTs) the acetolysis rates show a sharp increase. In the *endo*-compounds there is a corresponding sharp decrease in rate. An intermediate state has been suggested for these cases which electronically is somewhere intermediate between an allyl and a cyclopropyl cation.[68] With increasing n the allyl character becomes more important and it is probable that the *trans*-acetates are the first formed products. The addition of acetic acid to the double bond could then result in *trans* $\longrightarrow$ *cis* isomerisation to yield the observed *cis*-cyclenyl-3-acetates. The nature of this intermediate state has been the subject of a further communication.[69]

The addition of halogenocarbenes to double bonds is frequently employed as a first step in syntheses involving ring expansion. The implication of the above results is obvious. If a monohalogenocarbene is employed both *endo*- and *exo*-isomers are obtained, and if the bicyclic compound possesses few bridging atoms (n small) then only the *endo*-compound reacts to furnish the required product.[64,67] When the number of bridging atoms is large, then the *exo*-compound is the more reactive. In such circumstances it is preferable to employ a dihalogenocarbene so that an *endo*- and an *exo*-halogen is guaranteed. This method has formed the basis of a novel *meta*-cyclophane synthesis (24).[70] The *trans*-allylic system is readily accommodated by the medium-sized ring.[71]

The majority of the remaining thermally controlled electro-cyclic reactions of ($4n + 2$) π-electron systems correspond to the situation where n is unity, that is, the hexatriene–cyclohexadiene interconversion. The pentadienyl radical is also a

[67] M. S. Baird and C. B. Reese, *Tetrahedron Letters*, 1967, 1379; L. Ghosez, P. Laroche, and G. Slinckx, *ibid.*, p. 2767; L. Ghosez, G. Slinckx, M. Glineur, P. Hoct, and P. Laroche, *ibid.*, p. 2773; C. W. Jefford and R. Medary, *ibid.*, 1966, 2069, 2792; C. W. Jefford, E. H. Yen, and R. Medary, *ibid.*, p. 6317.
[68] U. Schöllkopf, K. Fellenberger, M. Patsch, P. von R. Schleyer, T. Su, and G. W. Van Dine, *Tetrahedron Letters*, 1967, 3639.
[69] von W. Kutzelnigg, *Tetrahedron Letters*, 1967, 4965.
[70] W. E. Parham and J. K. Rinehart, *J. Amer. Chem. Soc.*, 1967, **89**, 5668.
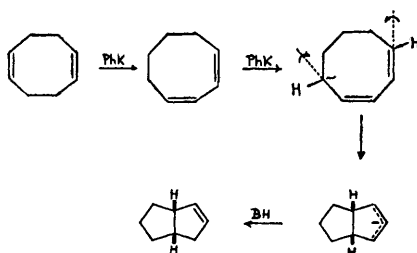[71] W. E. Parham and R. J. Sperley, *J. Org. Chem.*, 1967, **32**, 924, 926.
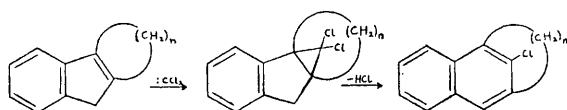
(24)

$n = 8$ or 10.

$(4n + 2)$ system, and is known to cyclise to give the cyclopentenyl radical.[72] The stereochemistry of the reaction has not been investigated. The pentadienyl anion, however, cyclises by the expected disrotatory mode (25).[73]
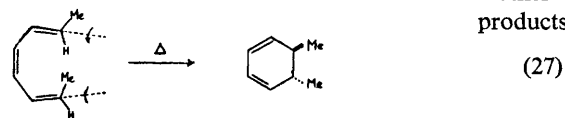
(25)

The thermal isomerisation of simple acyclic hexatrienes follows the expected disrotatory pathway even though the steric interactions [(26), (27)] between the incoming groups must be quite large.[74,75] This must be particularly true in the
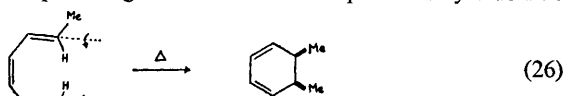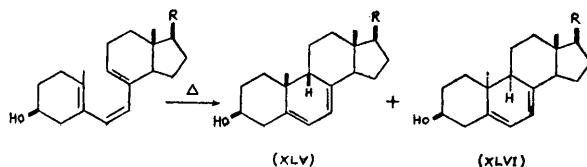
(26)

and
other
products

(27)

(XLV)   (XLVI)

(28)

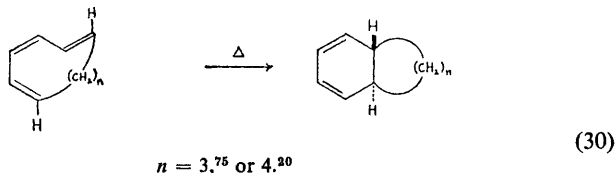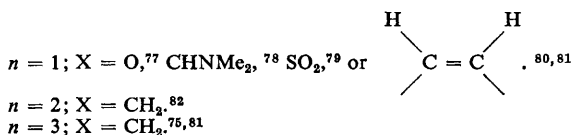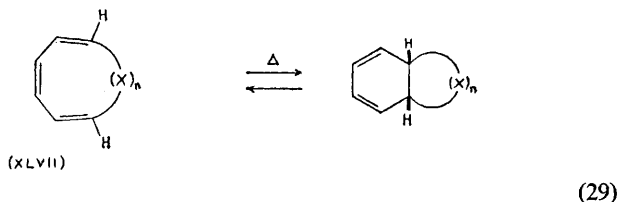[72] K. W. Egger and S. W. Benson, *J. Amer. Chem. Soc.*, 1966, **88**, 241.
[73] P. R. Stapp and R. F. Kleinschmidt, *J. Org. Chem.*, 1965, **30**, 3006.
[74] E. N. Marvell, G. Caple, and B. Schlatz, *Tetrahedron Letters*, 1965, 385.
[75] E. Vogel, W. Grimme, and E. Dinne, *Tetrahedron Letters*, 1965, 391.

well-known thermal conversion of precalciferol into isopyrocalciferol (XLV) and pyrocalciferol (XLVI).[76] It was here that Oosterhoff made the first suggestion of the possible importance of orbital symmetry relationships in such processes.[1a,76]

The hexatriene–cyclohexadiene interconversion is particularly easy when the 1,3,5-triene unit forms part of a ring system. Several of these processes are summarised in reactions (29) and (30). The cyclisations of the hexatrienes (XLVII; $n = 1$; $X = -O-$, $-N\lessgtr$, and $-CR_2-$) have been extensively studied.[75,77-82] The benzene oxide–oxepine equilibrium has been clearly established by nuclear magnetic resonance studies, and the equilibrium constant varies enormously with solvent polarity and to some extent with temperature.[77]

(29)

$n = 1$; $X = O,$[77] $CHNMe_2,$[78] $SO_2,$[79] or

 . [80,81]

$n = 2$; $X = CH_2.$[82]
$n = 3$; $X = CH_2.$[75,81]

(30)

$n = 3,$[75] or 4.[20]

However, azepines and simple cycloheptatrienes exist almost entirely in the monocyclic form (XLVII; $X = \gtrdot N\text{-}R$ or CH_2; $n = 1$). In the latter case the norcaradiene stability is favoured by the incorporation of one or both of the double bonds into a condensed aromatic system,[83] by bridging the C(1) and

[76] E. Havinga and J. L. M. A. Schlatmann, *Tetrahedron*, 1961, **16**, 146.

[77] E. Vogel, W. A. Böll, and H. Günther, *Tetrahedron Letters*, 1965, 609; H. Günther, *ibid.*, p. 4085; E. Vogel and H. Günther, *Angew. Chem. Internat. Edn.*, 1967, **6**, 385.

[78] A. P. Ter Borg, E. Razenberg, and H. Kloosterziel, *Rec. Trav. chim.*, 1966, **85**, 774.

[79] W. L. Mock, *J. Amer. Chem. Soc.*, 1967, **89**, 1281. Benzene is the product of the reaction, but it is probable that the bicyclic sulphone is intermediate in the change.

[80] R. Huisgen and F. Mietzsch, *Angew. Chem. Internat. Edn.*, 1964, **3**, 83; E. Vogel, H. Kiefer, and W. R. Roth, *ibid.*, p. 442.

[81] D. S. Glass, J. W. H. Watthey, and S. Winstein, *Tetrahedron Letters*, 1965, 377.

[82] A. C. Cope, A. C. Haven, F. L. Rampand, and E. R. Trumball, *J. Amer. Chem. Soc.*, 1952, **74**, 4867; see also ref. 43.

[83] R. Huisgen and G. Juppe, *Chem. Ber.*, 1961, **94**, 2332; E. Müller, H. Kessler, and H. Suhr, *Tetrahedron Letters*, 1965, 423; H. Nozaki, M. Yamabe, and R. Noyori, *Tetrahedron*, 1965, **21**, 1657; E. J. Corey, H. J. Burke, and W. A. Remers, *J. Amer. Chem. Soc.*, 1955, **77**, 4941; E. Vogel, D. Wendisch, and W. R. Roth, *Angew. Chem. Internat. Edn.*, 1964, **3**, 443.

C(6) positions with a three-atom bridge[84] (but not four- or five-atom bridges[77]), or by the presence of electron-withdrawing substituents at C(7).[85,86]

Norcaradienes which do not possess one of the above features are rare, but 2,5,7-triphenylnorcaradiene is reported to be moderately stable.[87] However, when the bridging atom spans the 9- and 10-positions of the naphthalene nucleus (XLVIII), the bicyclic 10π-electron systems (XLIX) are the predominant isomers (31).[77,88,89] The parent 10π-electron system [10]-annulene is not stable

(XLVIII)   (XLIX)

(31)

X = O,[88] CH₂,[89] N.CO.CH₃[88b]
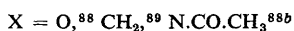
at normal temperatures and cyclises readily to *cis*-9,10-dihydronaphthalene, the expected isomer of a thermal reaction.

The Woodward–Hoffmann rules are therefore highly successful in the interpretation of the reactions of $4n + 2\pi$-electron systems run under thermal control. Occasionally the $(4n + 2)$ system involved in the change may only appear as a transient intermediate in the reaction, but its presence seems probable from the nature of the final product [*e.g.*, reactions (32)[29] and (33)[90]].
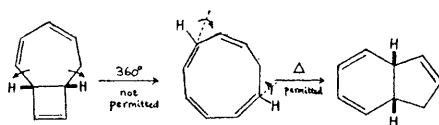
(32)
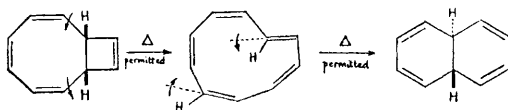
(33)

[84] E. Vogel, W. Wiedemann, H. Kiefer, and W. F. Harrison, *Tetrahedron Letters*, 1963; 673; P. Radlick and W. Rosen, *J. Amer. Chem. Soc.*, 1966, **88**, 3461; R. Darms, T. Threlfall, M. Pesaro, and A. Eschenmoser, *Helv. Chim. Acta*, 1963, **46**, 2893.

[85] E. Ciganek, *J. Amer. Chem. Soc.*, 1965, **87**, 652, 1149; M. A. Battiste and T. J. Barton, *Tetrahedron Letters*, 1967, 1227.

[86] E. Ciganek, *J. Amer. Chem. Soc.*, 1967, **89**, 1454, 1458.

[87] T. Mukai, H. Kubota, and T. Toda, *Tetrahedron Letters*, 1967, 3581.

[88] (a) A. Shani and F. Sondheimer, *J. Amer. Chem. Soc.*, 1967, **89**, 6310; (b) E. Vogel, N. Biskup, W. Pretzer, and W. A. Böll, *Angew. Chem. Internat. Edn.*, 1964, **3**, 642.

[89] E. Vogel and H. D. Roth, *Angew. Chem. Internat. Edn.*, 1964, **3**, 228.

[90] S. Mazamune, C. G. Chin, K. Hojo, and R. T. Seidner, *J. Amer. Chem. Soc.*, 1967, **89**, 4805; see also K. Grohmann and F. Sondheimer, *ibid.*, p. 7119.

(ii) *Photochemical control (conrotatory mode allowed).* Although the photochemical transformations of $4n + 2$ π-electron systems are well known, virtually all of the reactions are of the hexatriene–cyclohexadiene type (*i.e.*, $n = 1$) so that the diversity of the processes is not very great. The irradiation of *trans,cis, trans*-2,4,6-octatriene yields *trans*-5,6-dimethyl-1,3-cyclohexadiene.[91] On this basis it seems likely that the photochemical cyclisation of *cis*-stilbene and of related systems gives as the initial product a *trans*-4a,4b-disubstituted phenanthrene (L).[92–94] The stereochemistry about the newly formed σ-bond has not often been proven and in the simple cases (R = H) the lability of the photoproduct in the presence of traces of oxygen makes its isolation experimentally exceedingly difficult. With appropriate substitution these difficulties are partially avoided.[95]
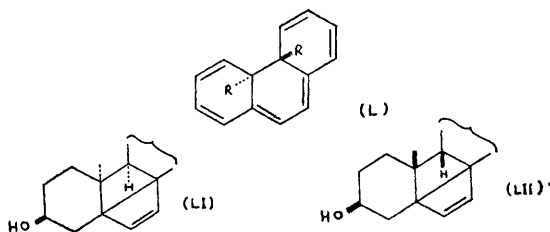
The photochemical ring fission of cyclohexadienes is well known and is frequently reversible. Occasionally the bridging of the butadiene unit to form a cyclobutene may occur in competition with the ring-opening to a hexatriene. The cyclobutene formation is not a photochemically reversible process since the absorbing chromophore is destroyed by the reaction.[91,96] Thus pyrocalciferol (XLVI) and isopyrocalciferol (XLV) upon irradiation yield the cyclobutenoid compounds (LI) and (LII) respectively.[97] However, ergosterol (LIII), which differs from the above only in the stereochemistry of the groups about the C(9)—C(10) bond, is converted into pre-ergocalciferol (LIV) which in turn is further transformed under the influence of light into tachysterol (LV) and lumisterol (LVI) as outlined in reaction (34).[98] The *cis*-ring fusion present in the pyrocalciferol and isopyrocalciferol molecules is much more amenable to cyclobutene formation than is the case for ergosterol or lumisterol which are *trans*-fused.

[91] G. J. Fonken, *Tetrahedron Letters*, 1962, 549.
[92] K. A. Muszkat and E. Fischer, *J. Chem. Soc.* (*B*), 1967, 662 and refs. therein.
[93] A. Padwa and R. Hartman, *J. Amer. Chem. Soc.*, 1966, **88**, 3759.
[94] C. E. Loader and C. J. Timmons, *J. Chem. Soc.* (*C*), 1967, 1343, 1457, 1677, and refs. therein.
[95] V. Boekelheide and J. B. Phillips, *J. Amer. Chem. Soc.*, 1967, **89**, 1695; J. B. Phillips, R. J. Molyneux, E. Sturm, and V. Boekelheide, *ibid.*, p. 1704; V. Boekelheide and T. Miyasaka, *ibid.*, p. 1709; H. Blashke and V. Boekelheide, *ibid.*, p. 2748.
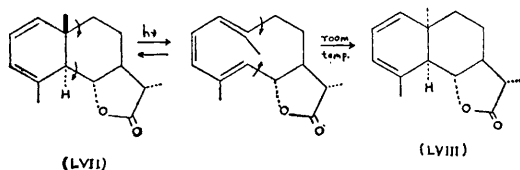[96] P. de Mayo and S. T. Reid, *Quart. Rev.*, 1961, **15**, 393.
[97] W. G. Dauben and G. J. Fonken, *J. Amer. Chem. Soc.*, 1959, **81**, 4060.
[98] E. Havinga, R. J. de Kock, and M. P. Rappoldt, *Tetrahedron*, 1960, **11**, 276.
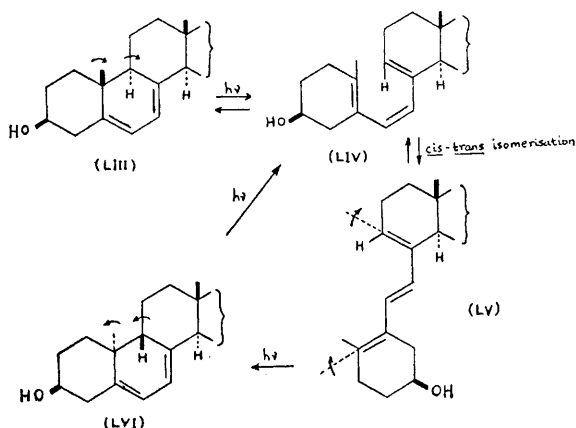
(34)

(35)

In some cases the conrotatory ring fission to give the hexatriene may be followed by a purely thermal (disrotatory) cyclisation process. A scheme based on these lines accounts for the photo-isomerisation of isodehydrocholesterol to coprosta-6,8-dienol[96] and for the conversion (LVII) ⟶ (LVIII).[99] The photochemical ring cleavages may, in suitable cases, be further complicated by thermally controlled sigmatropic rearrangement.[96,98,100] Such processes are considered below.

The conrotatory ring opening of 5,6-disubstituted cyclohexa-1,3-dienes under photochemical control should give a *cis,cis,trans*-hexatriene if the 5,6-substituents are *cis* to one another, whereas an all-*cis*-hexatriene or a *trans,cis,trans*-hexatriene should result with *trans*-5,6-substituents. In this connexion, Vogel and his collaborators[75] have found that (LIX) is isomerised to *cis,cis,trans*-cyclonona-1,3,5-triene which cyclises at room temperature by the disrotatory pathway to the *trans*-isomer of the starting material. Likewise (LX) yields (LXI),[75] and *trans*-9,10-dihydronaphthalene upon irradiation at very low temperatures gives detectable amount of [10]-annulene. Between −190° and room temperature the [10]-annulene cyclises (38) to *cis*-9,10-dihydronaphthalene.[101] One interesting

[99] E. J. Corey and A. G. Hortmann, *J. Amer. Chem. Soc.*, 1965, **87**, 5736.
[100] R. L. Autrey, D. H. R. Barton, A. K. Ganguly, and W. H. Reusch, *J. Chem. Soc.*, 1961, 3313.
[101] E. E. van Tamelen and T. L. Burkoth, *J. Amer. Chem. Soc.*, 1967, **89**, 151.

(36)

(37)

(38)
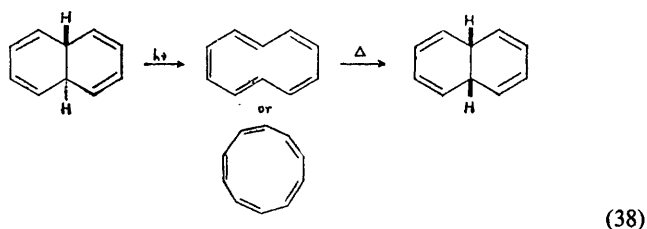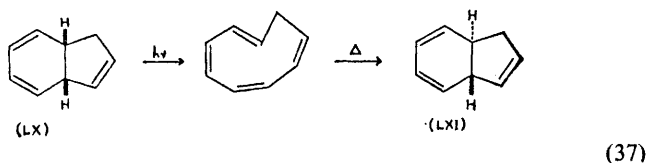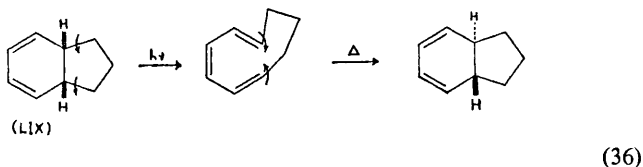
feature of reaction (37) is the simultaneous formation of *cis*-bicyclo[6,1,0]nona-2,4,6-triene[75] by a thermally controlled conrotatory cyclisation ($4n$ π-electron system).

2 Intramolecular Fragmentation Reactions

The concerted fragmentation reactions of olefinic systems are essentially the reverse of intermolecular addition reactions. Since the fragmentations have several features in common with these intermolecular additions, which are discussed below, and the intramolecular reactions outlined above, they may be conveniently considered here.

Basically some of the fragmentation reactions fit into the general pattern of reaction (39), where Y represents a group which furnishes one or more of its


(39)
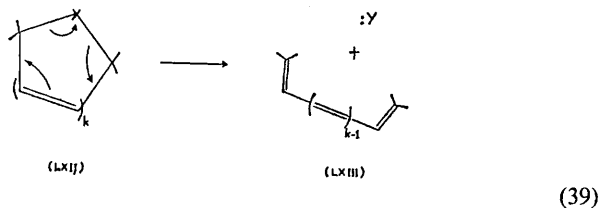
constituent atoms for the actual ring skeleton of (LXII). To deduce the orbital symmetry requirements it is simpler to consider the retro-reaction, that is, the

addition of :Y to the polyene (LXIII). The total number of electrons involved in the change (LXII) + :Y $\longrightarrow$ (LXIII) is $4 + 2(k - 1) + 2 = 2k + 4$, and comprises the four π-electrons of the terminal double bonds of (LXIII), the π-electrons of the internal (conjugated) double bonds of (LXIII), and the two electrons from Y which are here represented as a lone pair. If k is an even number, then the reaction is that of a $4n$ system which under thermal control should follow a conrotatory pathway. When k is odd, a disrotatory cyclisation of the $(4n + 2)$ system is to be expected in a thermally controlled reaction. In other words, if *half* the total number of electrons involved in the change is an even number the reaction is conrotatory, whereas if *half* the total number of electrons is odd the disrotatory mode is to be expected in thermal processes.

When k is zero the molecule (LXII) is a three-membered ring, and the theory predicts a non-concerted fragmentation with possible loss of stereospecificity.[2,102] Many of these thermal fragmentations are, however, highly stereospecific (LXII; $k = 0$; $Y = \overset{+}{>}N = \overset{-}{N}$, $>SO_2$, $>C = 0$, etc.), but this is not necessarily inconsistent with a non-concerted reaction pathway.[2,103]

The definitive cases are for the case $k = 1$, and a disrotatory cleavage is predicted. Thus the retro-Diels–Alder reaction provides ample evidence for this conclusion. One outstanding example of this process is provided by the ingenious synthesis (40) of benzocyclopropene.[103a] Here the group (Y) of (LXII) accommodates the pair of electrons in a newly-formed π-bond. When Y represents
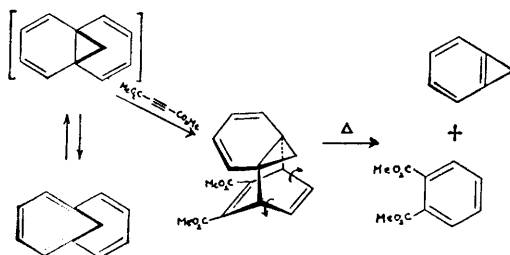
(40)

but a single ring-bonded atom, the two electrons must be accommodated as a non-bonding lone pair. Several examples of this type have been recently disclosed. Cyclopentadienone dimer upon heating to 120° suffers loss of carbon monoxide from the 10-position. The large positive entropy of activation ($\Delta S^{\ddagger} = 10$ e.u.) indicates a concerted reaction which, because of the geometry of the molecule, must follow a disrotatory pathway.[104] The thermally induced loss

[102] R. Hoffmann and R. B. Woodward, 150th National Meeting, American Chemical Society, Atlantic City, September 1965, Abstr. p. 8S; 151st National Meeting, American Chemical Society, Pittsburgh, March 1966, Abstr. A28, K109.

[103] J. P. Freeman and W. H. Graham, *J. Amer. Chem. Soc.*, 1967, **89**, 1761 and refs. therein; see also L. A. Paquette and L. S. Wittenbrook, *ibid.*, p. 4483.

[103] (a) E. Vogel, W. Grimme, and S. Korte, *Tetrahedron Letters*, 1965, 3625.

[104] J. E. Baldwin, *Canad. J. Chem.*, 1966, **44**, 2051.

of nitrogen and sulphur dioxide from (LXIV) and (LXV) occurs in similar stereospecific reactions (41), (42).[105–107] By the principle of microscopic rever-

(LXIV)

(41)

(LXV)

(42)

$$Y = \overset{+}{\underset{}{N}} = \overset{-}{N},^{105} \quad SO_2.^{106,107}$$
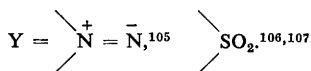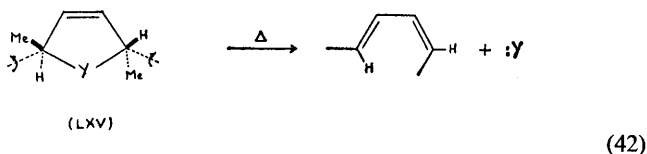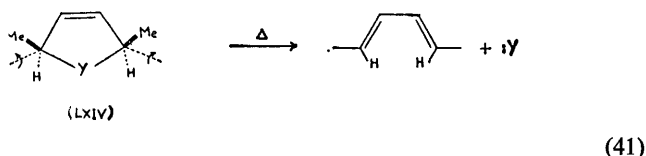
sibility, the retro-reactions should also be concerted and stereospecific. This is only possible chemically for the case of $Y = SO_2$, and has been entirely confirmed for the reverse of reaction (41).[106] The addition of sulphur dioxide to *cis,trans*-2,4-hexadiene requires more forcing conditions which results in some isomerisation.[106] The *trans*-cyclic compounds (LXV) require higher temperatures for complete reaction on account of the greater steric demand of the incoming methyl group at the transition state.

Fragmentation of (LXIV) and (LXV) under photochemical control should proceed by way of the conrotatory mode. It is difficult, however, to get sufficient energy into these molecules because of the nature of the absorbing chromophoric groups (*i.e.*, the energy required for the $\pi \longrightarrow \pi^*$ transition is very large). The problem can be overcome by the use of a sensitizer (*e.g.*, benzene). Thus (LXIV; $Y = SO_2$) upon sensitized irradiation yields the isomeric 2,4-hexadienes (LXVI), (LXVII) and (LXVIII) in the ratio 15:75:10, whereas with (LXV; $Y = SO_2$) the ratio is 60:25:15.[108] The evidence indicates that the fragmentation occurs mainly from an electronically excited triplet state before crossing to the

(LXVI)   (LXVII)   (LXVIII)
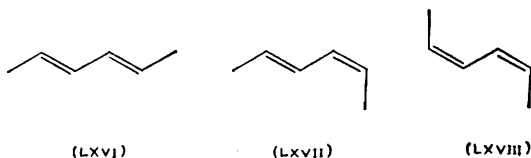
ground state. From (LXIV) and (LXV) (both $Y = SO_2$) the predicted products are respectively (LXVII) and (LXVI) which are the major components of the

[105] D. M. Lemal and S. D. McGregor, *J. Amer. Chem. Soc.*, 1966, **88**, 1335.
[106] S. D. McGregor and D. M. Lemal, *J. Amer. Chem. Soc.*, 1966, **88**, 2858.
[107] W. L. Mock, *J. Amer. Chem. Soc.*, 1966, **88**, 2857.
[108] J. Saltiel and L. Metts, *J. Amer. Chem. Soc.*, 1967, **89**, 2233.

mixtures of isomeric 2,4-hexadienes in each case. The other dienes are accounted for by *cis–trans* isomerisation initiated by electronically excited (triplet) SO_2 molecules. The results are therefore in accord with the expected conrotatory ring fission, but there is some uncertainty concerning the predictive power of the rules for electronically excited states of this nature. In a similar connexion, the electronic structure of trimethylenemethane produced by the thermal or photochemical decomposition of 4-methylene-1-pyrazoline has been discussed. The production of the ground-state triplet of trimethylenemethane by the photochemical process is in accord with the orbital symmetry arguments.[109]

The decomposition of the compounds (LXII, $k = 2$) have yet to be studied in detail. In the case of $Y = SO_2$ the indications are that reaction (39) is concerted in both forward and reverse directions. Thus *cis*-hexatriene and sulphur dioxide react at room temperature to give 2,7-dihydrothiepin 1,1-dioxide. The pyrolysis of the latter yields only the *cis*-hexatriene and sulphur dioxide.[79]

Other concerted cycloadditions have been examined theoretically.[2,102] An example is given by the generalised equation (43). It can be readily shown, by

$$R.CH_2-(CH=CH)_k-CH_2.R \rightarrow CH_2=CH-(CH=CH)_{k-1}-CH=CH_2 \\ + RR \qquad (43)$$
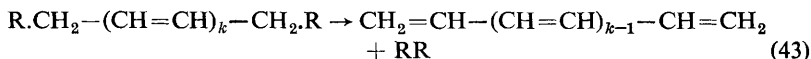
an adaptation of the group-theoretical approach of Longuet-Higgins and Abrahamson,[4] that concerted *cis*-elimination in reaction (43), which is characterised by a plane of symmetry (σ_{yz}) in the transition state (LXIX), is only allowable when k is an odd integer. When k is even or zero, concerted elimination is predicted to occur by way of a *trans*-mechanism, and the transition state (LXX) possesses a two-fold axis (C_{2v}) of symmetry. When k is even but small, the concerted *trans*-elimination may be exceedingly difficult since the close approach of the two groups R (to facilitate bonding) may cause a severe decoupling of the π-electron system. A similar situation pertains to ring systems


(LXIX)   (LXX)
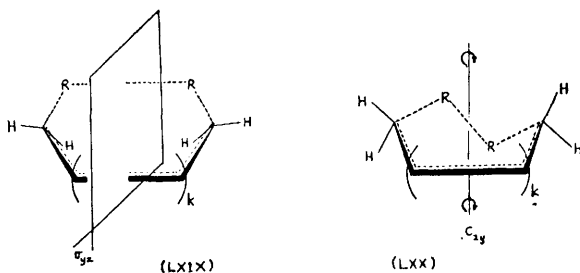
in which the groups R are situated *trans* to one another. The rules are precisely reversed for the photochemical reactions, and may also require further modification if inversion of geometry of the group R is a real possibility.

These conclusions are nicely demonstrated[41] by the pyrolyses of 1,4-cyclo-

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[109] W. T. Borden, *Tetrahedron Letters*, 1967, 259.

hexadiene and 1,3-cyclohexadiene. The first-named compound ($k = 1$ system) undergoes a smooth unimolecular conversion into benzene and hydrogen in a process of low activation energy. However, the 1,3-diene ($k = 2$ system) is converted into benzene and hydrogen only at high temperatures in a reaction in which radical intermediates are implicated.[110] The production of pyridines in the reaction of cyanogen and of related compounds with 1,3-dienes[111] may also proceed by way of the concerted 1,4-*cis*-elimination (44) of hydrogen from a dihydropyridine intermediate. The pyrolytic dehydrogenation of cyclopentene to cyclopentadiene also occurs predominantly by way of the symmetry-allowed
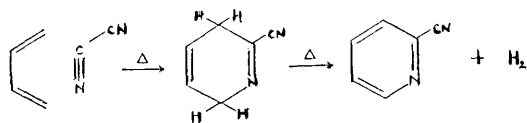
(44)

1,4-elimination.[112]

The hydrogen transfer from di-imide to the termini of polyenes has also been considered within the context of orbital symmetry relationships.[2,102] The reactions are formally similar to the reverse of (43) except that the two electrons of the imide $N=N$ must also be taken into account. Therefore the predictions are that 1,2-addition should be *cis* (a mode of addition which had been known for some time[113]) and 1,4-addition should be *trans* (not yet demonstrated).

Further concerted eliminations or additions might well yield to similar theoretical arguments. Fukui has outlined the relevance of his frontier orbital method to the consideration of stereospecific heterolytic and homolytic additions to multiple bonds.[3c]

### 3 Intermolecular Cycloaddition Reactions

The most common reactions in this category are dimerisations, although a few trimerisations and tetramerisations are known. The selection rules are most readily deduced (by calculation or by group-theoretical arguments) for cycloaddition reactions for which there is a plane of symmetry (σ_{xy}) at the transition state as in (LXXI), (LXXII) and (LXXIII).[1b] In the reactions new σ-bonds are formed equivalent in number to the π-bonds consumed. The number of olefinic π-electrons which participate in the reactions are given by the quantities p, q, and r. Hence the *total* number of π-electrons involved in the changes represented by (LXXI)—(LXXIII) are $(p + q)$, $(p + 2q)$, and $(p + q + 2r)$ respectively. In their simplest context, the symmetry rules require that for reactions run under

[110] R. J. Ellis and H. M. Frey, *J. Chem. Soc. (A)*, 1966, 553; S. W. Benson and R. Shaw, *Trans. Faraday Soc.*, 1967, **63**, 985; S. W. Benson and R. Shaw, *J. Amer. Chem. Soc.*, 1967, **89**, 5351.
[111] G. J. Janz, "1,4-Cycloaddition Reactions", ed. J. Hamer, Academic Press, London, 1967, p. 97.
[112] J. E. Baldwin, *Tetrahedron Letters*, 1966, 2953.
[113] C. E. Miller, *J. Chem. Educ.*, 1965, **42**, 254.

(LXXI) (LXXII) (LXXIII)

$2\pi \longrightarrow 2\sigma$ $3\pi \longrightarrow 3\sigma$ $4\pi \longrightarrow 4\sigma$
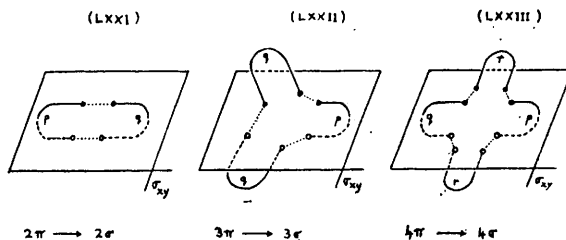
thermal control $\frac{1}{2}(p + q)$, $\frac{1}{2}(p + 2q)$, or $\frac{1}{2}(p + q + 2r)$ should be odd (*i.e.*, $4n + 2$ systems), whereas these quantities should equate to an even number (*i.e.*, $4n$ systems) for allowed photochemical processes. Actually, these conclusions are only correct for completely *cis*-additions on all components. In some cases the *trans*-addition of one or more of the olefinic components in the cycloaddition process may be possible, and the orbital symmetry requirements are accordingly modified. In triple or more complicated additions these topological

Table 2

$(p + q)$	Thermal	Photochemical
$4n$	*cis-trans*	*cis-cis*
	trans-cis	*trans-trans*
$4n + 2$	*cis-cis*	*cis-trans*
	trans-trans	*trans-cis*

distinctions can become very complex (*e.g.*, there are three distinct *cis–trans–trans* combinations), particularly when the symmetry plane is absent from the cycloaddition.[2] Completely *cis*-additions are assumed in the following discussion since *cis–trans*, or *trans–trans* additions are very uncommon.[2]

By convention the values $(p + q)$, $(p + 2q)$, or $(p + q + 2r)$ are used to classify the reactions so that $(4 + 2)$, $(6 + 4)$, and $(8 + 2)$ processes are allowed thermally, and $(2 + 2)$, $(4 + 4)$, and $(6 + 2)$ processes should only occur if one olefin is in the lowest electronically excited state. Likewise $(2 + 2 + 2)$ and $(2 + 2 + 2 + 2)$ are representative of a thermally allowed trimerisation, and a photochemically allowed tetramerisation, respectively. It is convenient to consider the thermal reactions first.

A. Thermally Controlled Cycloaddition Reactions.—$(4 + 2)$ *Reactions.* This group comprises the Diels–Alder reaction and related processes, which have been the subject of several reviews.[114–119] It is sufficient therefore to consider recent examples.

[114] J. Hamer ed., "1,4-Cycloaddition Reactions", Academic Press, London, 1967.
[115] A. Wassermann, "Diels–Alder Reactions", Elsevier, Amsterdam, 1965.
[116] R. Huisgen, R. Grashey, and J. Sauer, "Chemistry of the Alkenes", ed. S. Patai, Interscience, New York, 1964, p. 739.
[117] J. G. Martin and R. K. Hill, *Chem. Rev.*, 1961, **61**, 537.
[118] S. B. Needleman and M. C. Chang Kuo, *Chem. Rev.*, 1962, **62**, 405.
[119] M. A. Ogliaruso, M. G. Romanelli, and E. I. Becker, *Chem. Rev.*, 1965, **65**, 261.

In addition to the above selection rules in Table 2, Woodward and Hoffmann have deduced that (4 + 2) reactions should be characterised by *endo*-transition states.[1c] This result, which is in accord with experience, arises from a consideration of the secondary orbital interactions, a viewpoint which has been recently criticised.[120] Nevertheless, the facts remain and there are very few exceptions to the Alder *endo*-addition rule for reactions in which such a distinction may be drawn. One case of *exo*-addition arises in the reaction (45) of furan with maleic anhydride.[121] Further work has shown that the *endo*-isomer is also formed, but in solution and at moderate temperatures it is converted into the more stable *exo*-isomer by dissociation and recombination.[122] With maleic imide the stereo-

(45)
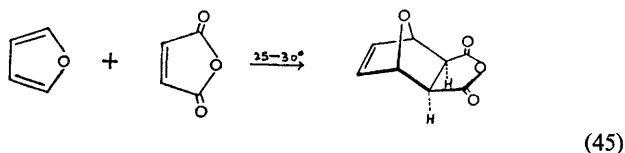
chemistry of the addition can be controlled more readily by the appropriate choice of reaction temperature.[123]

Cyclobutadienes also dimerise in a partially non-stereospecific manner since both *syn*- and *anti*-dimers are formed (reaction 46).[124] When the diene is generated by a non-ambiguous route, for example as from the cyclobutadiene–iron tricarbonyl complex, the amount of the *syn*-dimer far outweighs the amount of the *anti*-compound.[125] Cyclobutadiene is highly reactive both as a diene and as a

(46)
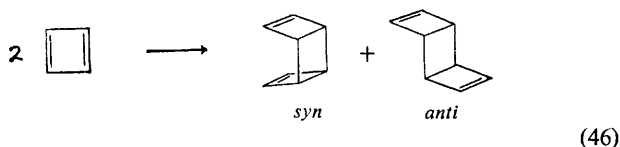
dienophile, and it is perhaps not surprising that the secondary interactions (if indeed they are important) are of only minor significance in the overall energy change. The iron tricarbonyl complex of cyclobutadiene is a particularly convenient source for the free diene, and a study of its reactivity towards various dienophiles has led Pettit and his co-workers to the discovery of several interesting and important preparative methods to compounds containing the cyclobutane ring. Typical examples include the synthesis of Dewar benzenes,[126] tricyclo[4,2,0,0^{2,5}]octa-3,7-dienes,[32] and cubane (reaction 47).[127]

[120] W. C. Herndon and L. H. Hall, *Tetrahedron Letters*, 1967, 3095.
[121] R. B. Woodward and H. Baer, *J. Amer. Chem. Soc.*, 1948, **70**, 1161.
[122] F. A. L. Anet, *Tetrahedron Letters*, 1962, 1219.
[123] H. Kwart and I. Burchuk, *J. Amer. Chem. Soc.*, 1952, **74**, 3094.
[124] R. Criegee, *Angew. Chem.*, 1962, **74**, 703 and refs. therein; P. S. Skell and R. J. Peterson, *J. Amer. Chem. Soc.*, 1964, **86**, 2530 and refs. therein.
[125] L. Watts, J. D. Fitzpatrick, and R. Pettit, *J. Amer. Chem. Soc.*, 1966, **88**, 623.
[126] L. Watts, J. D. Fitzpatrick, and R. Pettit, *J. Amer. Chem. Soc.*, 1965, **87**, 3253.
[127] J. B. Barborak, L. Watts, and R. Pettit, *J. Amer. Chem. Soc.*, 1966, **88**, 1328.
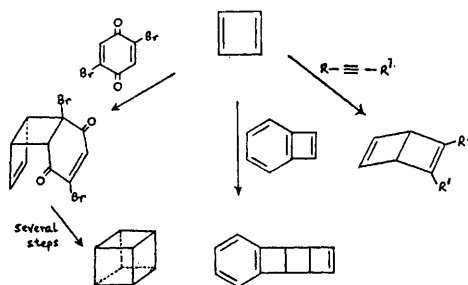
(47)

In recent years development of the Diels–Alder reaction as a general synthetic method has frequently led to the use of less conventional dienes (*e.g.*, cyclobutadiene) and dienophiles. The nitrogen analogue of *N*-phenylmaleimide (LXXIV) has been reported to be a potent dienophile,[128] and the reactivity of cyclopropenes[129] and cyclopropanones[130–131] has attracted some attention. The cyclopropanones most probably react as the enolate dipole, and upon reaction with dienes cyclic 7-membered ring ketones can be prepared. The reaction of 1,2-dibromo-1,2-diphenylpropan-2-one with sodium iodide in acetonitrile in the presence of furan yields a mixture of the *cis*- and *trans*-adducts (LXXV) and (LXXVI).[131] A possible reaction pathway can be formulated as in (48), but the experimental results are not inconsistent with a non-concerted mechanism. In any event, if the reaction is concerted the observed stereospecificity cannot be
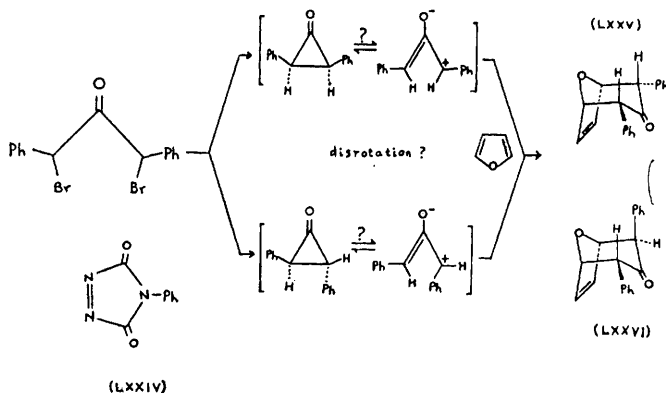
(48)

accounted for by the symmetry-allowed secondary interactions of energy levels since such an interaction is not possible in these cases.[131]

[128] R. C. Cookson, S. S. H. Gilani, and I. D. R. Stevens, *J. Chem. Soc.* (*C*), 1967, 1705.
[129] For example see: H. Tanida, T. Tsuji, and T. Irie, *J. Amer. Chem. Soc.*, 1967, **89**, 1953; M. A. Battiste and T. J. Barton, *Tetrahedron Letters*, 1967, 1227.
[130] W. B. Hammond and N. J. Turro, *J. Amer. Chem. Soc.*, 1966, **88**, 2880.
[131] R. C. Cookson, M. J. Nye, and G. Subrahmanyan, *J. Chem. Soc.* (*C*), 1967, 473.

The product of the thermal reaction of tetracyanoethylene and *N*-ethoxy-carbonylazepine was originally assigned the structure (LXXVII), a $(6 + 2)$ adduct.[132] On the basis of spectroscopic and *X*-ray studies, the structure has
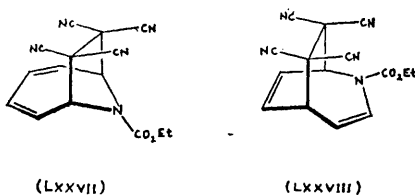
(Lxxvii)   (Lxxviii)

been amended to (LXXVIII), the thermally allowed $(4 + 2)$ adduct.[133] A similar conclusion has been recorded for the adducts derived from *N*-methoxy-carbonylazepines,[134] and also from 3-bromo-*N*-methoxycarbonylazepine.[135]

The irradiation of tropone in ether or acetonitrile solution yields, among other products, a $(4 + 2)$ dimer.[136,137] Since this is a disallowed process, it seems probable that this product arises from a reaction involving the addition of a *trans* or Möbius-type tropone molecule to a second molecule of tropone in the ground state.[137] Alternatively the process may be non-concerted.[138]

The considerations of orbital symmetry are not necessarily restricted to the reactions of neutral stable molecules, but encompass the concerted reactions of radicals and of anions and cations. Thus, reactions (49) and (50) are allowed thermal processes of the $(4 + 2)$ type, whereas (51) is a $(2 + 2)$ reaction and should not occur under thermal control. The thermolysis of perezone (LXXIX)

(49)

(50)

(51)
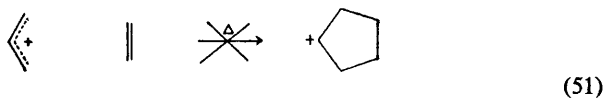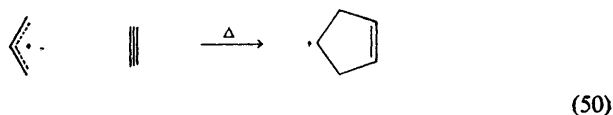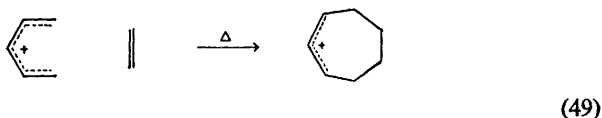
[132] K. Hafner, *Angew. Chem. Internat. Edn.*, 1964, **3**, 165.
[133] J. H. van den Hende and A. S. Kende, *Chem. Comm.*, 1965, 384.
[134] J. E. Baldwin and R. A. Smith, *J. Amer. Chem. Soc.*, 1965, **87**, 4819.
[135] R. A. Smith, J. E. Baldwin, and I. C. Paul, *J. Chem. Soc.* (*B*), 1967, 112.
[136] A. S. Kende, *J. Amer. Chem. Soc.*, 1966, **88**, 5026.
[137] T. Tezuka, Y. Akasaki, and T. Mukai, *Tetrahedron Letters*, 1967, 1397, 5003.
[138] A. S. Kende and J. E. Lancaster, *J. Amer. Chem. Soc.*, 1967, **89**, 5283; G. R. Ziegler and G. S. Hammond, *ibid.*, 1968, **90**, 513.

to the pipetzols (LXXX)[139] is most probably a reaction of type (49),[41] although the allowed (2 + 2 + 2) process [(53); see later] cannot be entirely discounted as an alternative pathway. The hydroxycyclopropanone product (LXXXI)

(52)

(53)
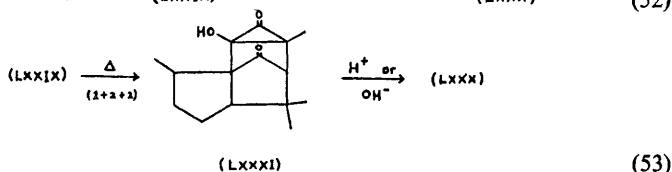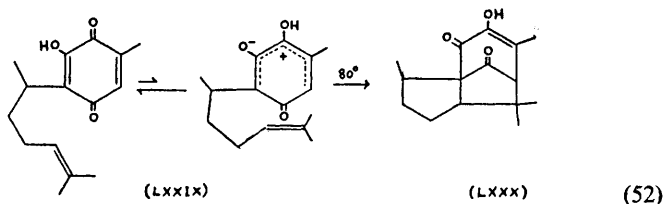
might readily be converted into (LXXX) in the presence of fortuitous acidic or basic impurities.

The ene synthesis[140] is related to the Diels–Alder reaction in that it is essentially a (4 + 2) cycloaddition which requires the movement (54) of the double bond in the ene or diene. The predictable *endo*-addition[41] has been observed for the reactions of *cis*-but-2-ene, cyclopentene, and *trans*-but-2-ene. The *cis*-olefins

(54)
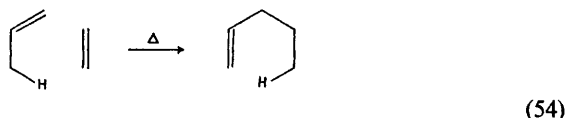
yield mainly the *threo*-adduct, whereas for the *trans*-olefin the major adduct has the *erythro*-configuration.[141]

(6 + 4) *Reactions*. Since the publication of the Woodward–Hoffmann rules, a few examples of (6 + 4) thermal cycloadditions have been reported. It is perhaps significant, in view of the recent criticism[120] of the suggestion that the product stereochemistry is dependent upon secondary orbital interactions in the transition state, that the predicted *exo*-cycloaddition occurs in all cases. Clearly, further theoretical approaches are required before it becomes known if these criticisms are justified.

In (6 + 4) reactions, the operation of highly adverse entropy effects are likely to be of crucial importance to the possible occurrence of such reactions. It is not surprising, therefore, that in all of the known (6 + 4) cycloadditions

[139] E. R. Wagner, R. D. Moss, R. M. Brooker, J. P. Heeschen, W. J. Potts, and M. L. Dilling, *Tetrahedron Letters*, 1965, 4233.
[140] W. R. Roth, *Chimia*, 1966, **20**, 229.
[141] J. A. Berson, R. G. Wall, and H. D. Perlmutter, *J. Amer. Chem. Soc.*, 1966, **88**, 187.

the reacting systems are embedded within rings. In this way, the termini of the olefins are held close enough together, for sufficient time, for the reaction to proceed at a useful rate.

The reaction of cyclopentadiene with tropone gives the *exo*-adduct (LXXXII),[142] and similarly 2,5-dimethyl-3,4-diphenylcyclopentadienone reacts with tropone and cycloheptatriene to furnish (LXXXIII) and (LXXXIV) respectively.[41]


(LXXII): R = R′ = H; X = CH₂

(LXXXII): R = R′ = H; X = CH$_2$

(LXXXIII): R = Me; R′ = Ph; X = >C = O

A product arising from the *cis* (6 + 6) dimerisation of *N*-ethoxycarbonyl-azepine is formed at 200°. This anomalous compound arises from the thermal rearrangement of the initially formed (4 + 2) dimer (LXXXV), which can be isolated at lower (130°) temperatures.[143] Other *N*-substituted azepines yield (6 + 6) dimers upon thermolysis, and the intermediacy of the (6 + 4) adduct has also been demonstrated for the cyano-compound (LXXXV; −CO₂.Et = CN).[144] The *cis* (6 + 4) compound obtained by the irradiation of tropone in acetonitrile is formed in a non-concerted reaction.[138]

(8 + 2) *Reactions.* In the only reactions of this type which have been observed four of the π-bonds have been conformationally frozen within ring structures. 5,6-Dimethylenecyclohexa-1,3-diene, which can be generated by the pyrolysis of the thiophen dioxide (LXXXVI), reacts with *N*-phenylmaleimide to give the imide (LXXXVII).[145] The thermolysis of the cyclobutene (LXXXVIII) in the

[142] R. C. Cookson, B. V. Drake, J. Hudec, and A. Morrison, *Chem. Comm.*, 1966, 15; S. Ito, Y. Fujise, T. Okuda, and Y. Inone, *Bull. Chem. Soc. Japan*, 1966, **39**, 1351.
[143] L. A. Paquette and J. H. Barrett, *J. Amer. Chem. Soc.*, 1966, **88**, 2590.
[144] A. L. Johnson and H. E. Simmons, *J. Amer. Chem. Soc.*, 1966, **88**, 2591; 1967, **89**, 3191,
[145] M. P. Cava and A. A. Deana, *J. Amer. Chem. Soc.*, 1959, **81**, 4266.

presence of maleic anhydride to give (LXXXIX)[146] is essentially a similar reaction. Of interest is the stereochemistry of the product (LXXXIX). If *cis*-addition in the final step is assumed, then ring-opening of the cyclobutene must occur by the expected conrotatory pathway. The reaction between 7-methylenecyclohepta-1,3,5-triene and dimethyl acetylenedicarboxylate furnishes the azulene

(LXXXVIII)   (LXXXIX)

(56)

(XC)

(XCI)
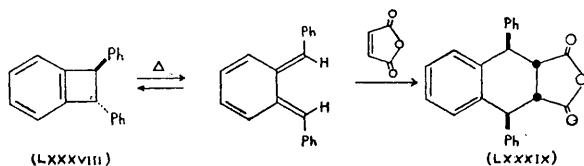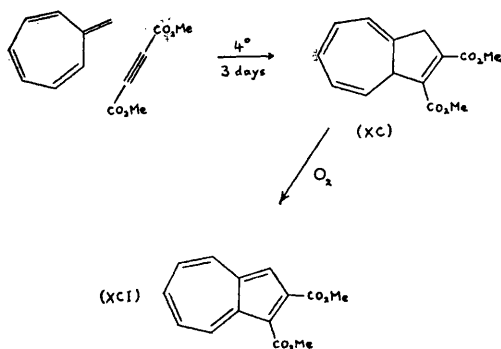
(57)

(XCI) when the reaction mixture is worked up in the presence of oxygen.[147] That the (8 + 2) cycloadduct (XC) is formed initially is therefore highly probable.[41]

The treatment of 1,2,3,4,5,6-hexaphenylpentalene with excess of dimethyl acetylenedicarboxylate at 160° gives a diethoxycarbonylhexaphenylazulene, formulated as (XCII, a or b).[148] The reaction most probably involves an initial (8 + 2) addition,[41] followed by the fission of the cyclobutene ring. If these considerations are correct, then the product should be (XCIIa).

Thermal cycloadditions of order higher than (8 + 2). The only reaction of this type which has come to the Reviewer's attention is that which occurs between bicyclohepta-2,4,6-triene-1-ylidene and tetracyanoethylene. The product (XCIII) has clearly been derived from a *trans* (14 + 2) cycloaddition reaction.[149] The orbital symmetry requirements are precisely reversed for *trans*-cycloadditions

[146] R. Huisgen and H. Seidl, *Tetrahedron Letters*, 1964, 3381.

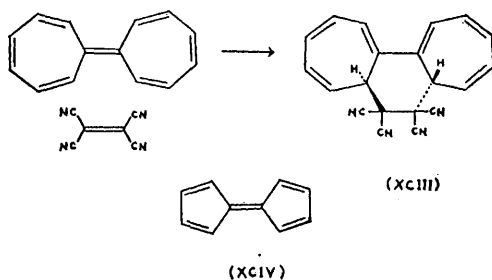[147] W. von E. Doering and D. W. Wiley, *Tetrahedron*, 1960, **11**, 183.

[148] E. Le Goff, *J. Amer. Chem. Soc.*, 1962, **84**, 3975.

[149] W. von E. Doering *et al.*, cited in ref. 41.

(58)
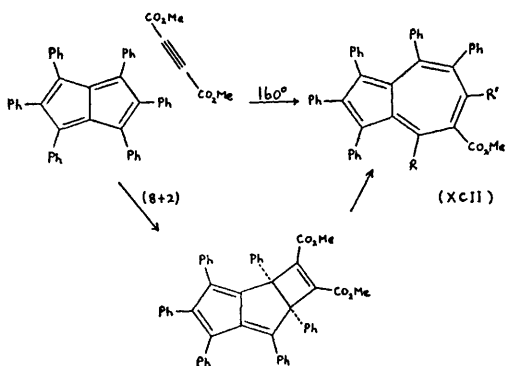
(a) R = Ph, R′ = CO₂Me
(b) R = CO₂Me, R′ = Ph

(59)

so that (59) is a symmetry-allowed process. However, the treatment of bicyclo-penta-2,4-dien-1-ylidene (XCIV) with tetracyanoethylene does not yield a (10 + 2) adduct, but instead a product resulting from a double Diels–Alder (4 + 2) process.[150] The required *trans* (10 + 2) cycloaddition is probably not possible for the less flexible fulvalene system, but the *cis* (10 + 2) photochemical addition seems feasible.

7,8-Dimethylenecyclo-octa-1,3,5-triene reacts readily with various dienophiles by addition across the exocyclic double bonds. The *cis*-fused adducts (*i.e.*, when maleic anhydride or *p*-benzoquinone are the dienophiles)[151] are formed by way of a (4 + 2), and not the disallowed (10 + 2), addition. The failure of attempted reactions of 1,2-diphenyl-3,4-methylenecyclobutene with dienophiles[152] may be now ascribed to the operation of an adverse orbital symmetry requirement for the (6 + 2) thermal processes.

[150] W. von E. Doering, U.S. Dept. Com., Office Tech. Serv., P.B. Rept., **34**, No. 3, 8 pp., 1960; *Chem. Abs.*, 1962, **56**, 5883e.
[151] J. A. Elix, M. V. Sargent, and F. Sondheimer, *Chem. Comm.*, 1966, 508.
[152] A. T. Blomquist and Y. C. Meinwald, *J. Amer. Chem. Soc.*, 1957, **79**, 5316.

(2 + 2 + 2) *Reactions*. The probability of a termolecular collision of three ethylenic molecules in the precise orientation and with sufficient energy to undergo a cyclic trimerisation is negligible. It is therefore necessary that at least two of the olefinic systems be held within a fairly rigid cyclic molecular framework and in the correct relative orientation. Most of the examples are provided by the reactions of dienophiles with norbornadiene.[153] The observed *endo*-addition (60)[154] is in agreement with the orbital symmetry arguments. 1,3,5,7-
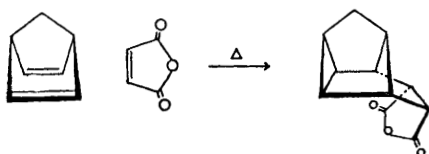
(60)

Tetramethylenecyclo-octane, a less rigid system, reacts with tetracyanoethylene by a similar (2 + 2 + 2) mechanism (61).[155]
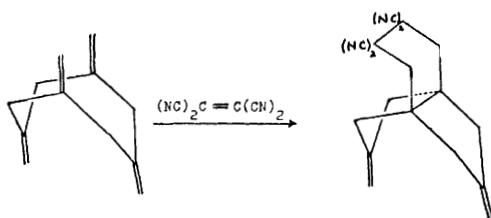
(61)

B. Photochemically Controlled Cycloaddition Reactions.—The photochemical cycloadditions leading to carbocyclic systems have been recently reviewed,[44,116,156] so few examples will be considered here.

(2 + 2) *Reactions*. There is a dearth of examples for the photodimerisation of simple acyclic ethylenic compounds as in reaction (62).[157] Rather more common are the (2 + 2) reactions of acyclic non-conjugated olefins in which both of the
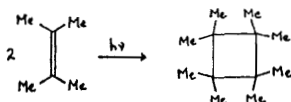
(62)

[153] A. T. Blomquist and Y. C. Meinwald, *J. Amer. Chem. Soc.*, 1959, **81**, 667; H. Heaney and J. M. Jablonski, *Tetrahedron Letters*, 1967, 2733; F. W. Grant, R. W. Gleason, and C. H. Bushweller, *J. Org. Chem.*, 1965, **30**, 290.
[154] R. C. Cookson, J. Dance, and J. Hudec, *J. Chem. Soc.*, 1964, 5416.
[155] J. K. Williams and R. E. Benson, *J. Amer. Chem. Soc.*, 1962, **84**, 1257.
[156] W. L. Dilling, *Chem. Rev.*, 1966, **66**, 373.
[157] D. R. Arnold and V. Y. Abraitys, *Chem. Comm.*, 1967, 1053.

π-systems belong to the same molecule,[156] and the photodimerisation of conjugated and small cyclic olefins.[44,116,156,158,159] Energy transfer, frequently a thorny problem, is often achieved by the use of a sensitizer, and dimerisation may then occur by way of the triplet state.[44,157,158]

The $(2 + 2)$ photo-cycloaddition reaction is particularly useful in the synthesis of cage compounds.[44,116,157,158] Thus, norbornadiene, its derivatives, and related compounds undergo ready cycloaddition to quadricyclenes upon direct or sensitized irradiation.[44,116,158,160] Reaction (63) is a recent example of this
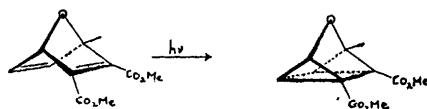
(63)

type of process.[161] In a similar manner, $(2 + 2)$ photochemical reactions have facilitated the synthesis of cubanes,[127] homocubanes,[162] and 'basketanes',[163] besides a whole host of other types of cage compounds.[44,116,156,158]

Benzene, a molecule which does not yield to the Diels–Alder reaction, can be persuaded to react photochemically with dimethylacetylenedicarboxylate and related compounds,[44,158,164] for example, reaction (64). The intermediate $(2 + 2)$ adduct (XCV) is implicated in these reactions. On the other hand, the reactive
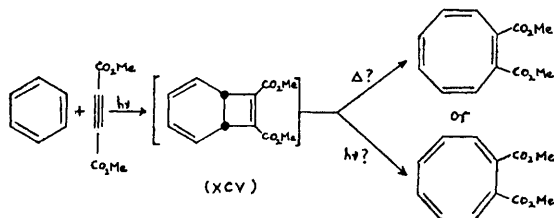
(64)

diene, cyclopentadiene, will react in the $(2 + 2)$ manner with dichloromaleic anhydride.[165]

[158] O. L. Chapman, *Adv. Photochem.*, 1963, **1**, 323.

[159] R. Srinivasan, *Adv. Photochem.*, 1964, **4**, 113.

[160] S. J. Cristol and R. L. Snell, *J. Amer. Chem. Soc.*, 1958, **80**, 1950; G. S. Hammond, N. J. Turro, and A. Fisher, *ibid.*, 1961, **83**, 4674; P. G. Grassman, D. H. Aue, and D. S. Patton, *ibid.*, 1964, **86**, 4211; D. M. Lemal, E. P. Gosschlink, and S. D. McGregor, *ibid.*, 1966, **88**, 582; W. G. Dauben and R. L. Cargill, *Tetrahedron*, 1961, **15**, 197; H. Prinzbach, W. Eberbach, and G. von Veh, *Angew. Chem. Internat. Edn.*, 1965, **4**, 436.

[161] E. Payo, L. Cortés, J. Mantecón, C. Rivas, and G. de Pinto, *Tetrahedron Letters*, 1967, 2415.

[162] J. C. Barborak and R. Pettit, *J. Amer. Chem. Soc.*, 1967, **89**, 3080.

[163] S. Masamune, H. Cuts, and M. G. Hogben, *Tetrahedron Letters*, 1966, 1017; W. G. Dauben and D. L. Whalen, *ibid.*, p. 3743.

[164] E. Grovenstein and D. V. Rao, *Tetrahedron Letters*, 1961, 148; D. Bryce-Smith and J. E. Lodge, *Proc. Chem. Soc.*, 1961, 333; *J. Chem. Soc.*, 1963, 695.

[165] H.-D. Scharf, *Tetrahedron Letters*, 1967, 4231.

The concerted $(2 + 2)$ reactions should, according to the Woodward–Hoffmann rules, occur only under photochemical activation (*cis*-addition assumed), a condition which also applies to the retro-reactions. Of course, not all reactions which yield cyclobutanes and cyclobutenes are concerted, and many proceed under purely thermal control by way of biradical or dipolar intermediates.[116,166,167] However, some thermal $(2 + 2)$ reactions have been reported which appear to be concerted processes. In each case a *d*-electron metal atom is present, and the processes are symmetry-allowed on account of the interaction of olefin and metal electronic energy levels.[30] Thus quadricyclene is rapidly converted into norbornadiene in the presence of various complexes of platinum, palladium, and rhodium.[31a] Similarly μ-dichlorohexamethylbicyclo[2, 2, 0]hexa-2,5-dienedirhodium catalyses the conversion of hexamethylprismane into hexamethylbicyclo[2,2,0]hexa-2,5-diene.[31b] The reaction of iron or ruthenium tricarbonyl complexes with hexafluoroacetone (XCVI; $Y = 0$) and with 1,1-dicyano-2,2-bis(trifluoromethyl)ethylene [XCVI; $Y = C(CN)_2$] gives the corresponding $(2 + 2)$ adducts (XCVII).[168]

(65)
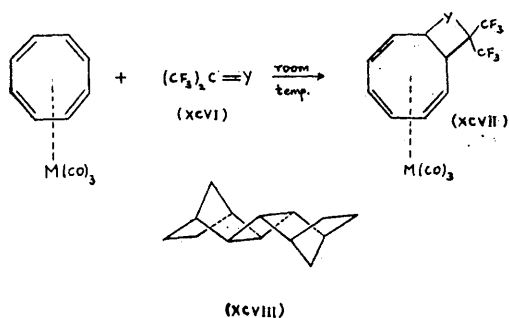
The conversion of norbornene into the *exo,trans,exo*-dimer (XCVIII) only occurs if both a cuprous salt (*e.g.*, Cu_2Br_2) and irradiation are employed. Apparently a termolecular collision is required, and this prerequisite is accounted for in terms of an electronically excited tetrahedral copper complex containing three molecules of norbornene and one halogen atom.[169] If the reaction is concerted, then an interesting point can be raised: is the $(2 + 2)$ stereospecific reaction subject to thermal control with the involvement of the metal atom, or is the process essentially photochemical? The answer presumably depends upon the electronic configuration of the norbornene–cuprous bromide complex formed concomitantly with (XCVIII).

[166] J. D. Roberts and C. M. Sharts, *Org. Reactions*, 1962, **12**, 1.
[167] P. D. Bartlett *et al.*, *J. Amer. Chem. Soc.*, 1964, **86**, 616, 622, 628.
[168] M. Green and D. C. Wood, *Chem. Comm.*, 1967, 1062.
[169] D. J. Trecker, R. S. Foote, J. P. Henry, and K. E. McKeon, *J. Amer. Chem. Soc.*, 1966, **88**, 3021.

(4 + 4) *Reactions.* The photodimerisation of 2-pyridones,[170] α-pyrones,[171] 2-methoxynaphthalene,[172] and anthracenes[173] by formal (4 + 4) processes are well known.[158] The dimers are obtained by *cis*-addition across the positions indicated in (XCIX)—(CII). The reaction of benzene with butadiene to give (CIII) is a more recent case of this type of reaction.[174] The seemingly (4 + 4) dimerisation of 1,3-butadienes in the presence of nickel salts is now known to

(XCIX)   (C)   (CI)   (CII)

(CIII)

(66)

(67)
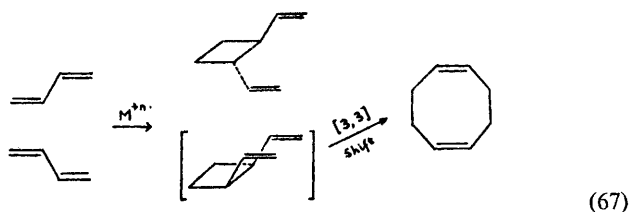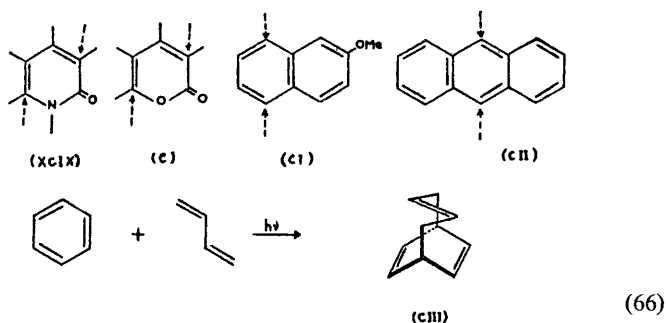
involve two discrete steps: a (2 + 2) metal-catalysed reaction followed by a Cope rearrangement (67).[175]

(6 + 2) *Reactions.* This is a very rare type of process. The irradiation of solutions of tropone yields a (6 + 2) dimer among other products,[136,137] but the cycloaddition may not be concerted.[138] Ziegler and Hammond have described a (6 + 2) cycloaddition in the photorearrangement of 1,4-epoxy-1,4-dihydro-naphthalene to benz[*f*]oxepin.[138a]

(6 + 6) *Reactions.* The irradiation of a dilute sulphuric acid solution of tropone yields the dimer (CIV).[137]

C. Metal-catalysed Cyclo-oligomerisations.—The Reppé cyclo-octatetraene synthesis, which is thought to involve the concerted tetramerisation of acetylene,

[170] L. A. Paquette and G. Slomp, *J. Amer. Chem. Soc.*, 1963, **85**, 765.

[171] P. de Mayo and R. W. Yip, *Proc. Chem. Soc.*, 1964, 84 and refs. therein.

[172] T. S. Bradshaw and G. S. Hammond, *J. Amer. Chem. Soc.*, 1963, **85**, 3953; see also E. Vogel, W. Grimme, W. Meckel, and H. J. Riebel, *Angew. Chem. Internat. Edn.*, 1966, **5**, 590; W. von E. Doering and J. W. Rosenthal, *J. Amer. Chem. Soc.*, 1966, **88**, 2078.

[173] D. E. Applequist and R. Searle, *J. Amer. Chem. Soc.*, 1964, **86**, 1389.

[174] K. Kraft and G. Koltzenburg, *Tetrahedron Letters*, 1967, 4357.

[175] E. Vogel, *Annalen*, 1958, **615**, 1; see also G. Satori, V. Turba, A. Valvassori, and M. Riva, *Tetrahedron Letters*, 1966, 211.

(cIV)   (cV)
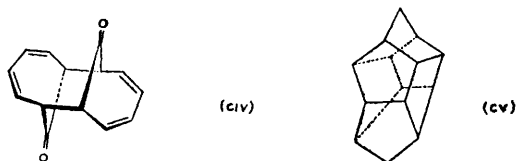
has been considered in the context of a symmetry-allowed thermal $(2 + 2 + 2 + 2)$ reaction in which the metal electronic energy levels are intimately implicated.[30] The trimerisation of 1,3-butadiene to cyclododeca-1,5,9-triene under similar circumstances[176] is possibly a $(4 + 4 + 4)$ process. The dimerisation of norbornadiene to (CV) in the presence of iron pentacarbonyl and light[177] appears to be an obvious $(2 + 2 + 2 + 2)$ reaction, but the precise nature of the involvement of the metal atom is not known.

4 Sigmatropic Rearrangements

A sigmatropic change is one which involves the migration of a σ-bond, flanked by one or more π-electron systems, to a new position within the molecule in an uncatalysed intramolecular process. The reaction order of these rearrangements is dependent upon the relationship of the σ-bond to the termini of the π-system(s). Reaction (68) is classified as a sigmatropic shift of order $[1, j]^{1d}$ since the group R′ migrates from C(1) to C(*j*). On the other hand, the reaction represented by
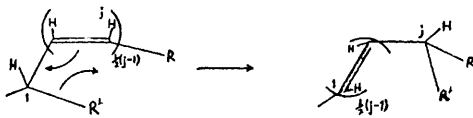
$$(68)$$

(69) is one of order $[i, j]^{1e}$ since the σ-bond which is cleaved is that joining C(*i*) and C(*j*). In the latter instance, the carbon framework is numbered starting from the terminus of each π-system. Thus (CVI) is representative of the transition
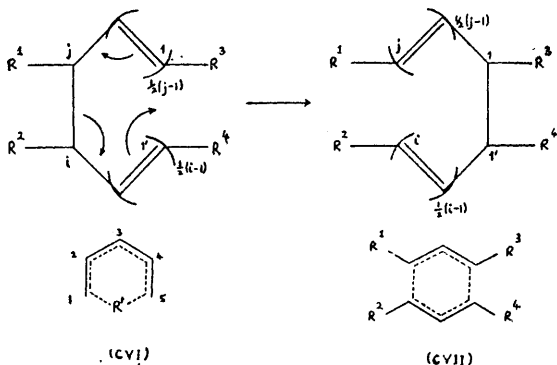
(CVI)   (CVII) (69)

[176] G. Wilke, *Angew. Chem. Internat. Edn.*, 1963, **2**, 105.
[177] D. M. Lemal and K. S. Shim, *Tetrahedron Letters*, 1961, 368; C. W. Bird, D. L. Colinese, R. C. Cookson, J. Hudec, and R. O. Williams, *ibid.*, p. 373.

state of a [1, 5] shift, whereas (CVII) illustrates that for a [3, 3] rearrangement.

A. Sigmatropic Rearrangements of Order [1, *j*].—The orbital symmetry argu-
ments are based upon the assumption that these systems [*e.g.*, (CVI)] can be
treated as a pair of interacting radicals, namely R′ and the framework radical.
By the above definition, the radical(s) derived from the carbon framework must
be of the odd–alternant type, and will therefore possess one non-bonding
electronic energy level. In thermal reactions this level is occupied by the odd
electron, and Figure 3 represents the general symmetry properties of the orbital.
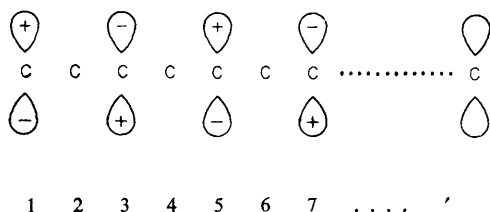
Figure 3

On account of the non-bonding property, the wave function has nodes at the
even-numbered carbon nuclei.

Two different transition-state geometries have been defined for [1, *j*] sigma-
tropic rearrangements.[1d] In the *suprafacial* route the migrating atom or group
(R′) is associated at all times with the same face of the π-system; in the *antara-
facial* process the migrating group (R′) is passed from the top face of one carbon
terminus to the bottom face of the other.

Assuming that the migrating atom or group (R′) employs a σ-type orbital,
Figure 3 reveals that [1, 3], [1, 7], [1, 11] . . . . shifts [*i.e.*, $\frac{1}{2}(j - 3)$ is zero or
even] must be antarafacial, whereas [1, 5], [1, 9] . . . . shifts [*i.e.*, $\frac{1}{2}(j - 3)$ is
odd] must occur by the suprafacial route.[1d]

Clearly all [1, 3] antarafacial shifts will be impossible, as will be [1, *j*] antara-
facial shifts in rings of moderate size, on account of the serious uncoupling of
the polyenyl radical orbitals.

In reactions involving the first excited state, concerted shifts are governed by
rules which are precisely the reverse of the above. This arises from the different
symmetry properties of the lowest excited-state levels of the polyenyl radicals.

Thermal [1, 3] *shifts (antarafacial)*. As might be expected, there is no known
example for the migration of σ-type radicals (*e.g.*, H). Berson and Nelson have
found that the thermolysis of [*exo*-^{2}H$_7$]bicyclo[3,2,0]hept-2-en-*endo*-6-yl acetate
(CVIII) yields *exo-cis*-6-deuterionorborn-2-en-5-yl acetate (CIX), a reaction which
involves the concerted *suprafacial* migration (70) of a π-type radical.[178] In
π-type migrations, in which the selection rules are precisely reversed owing to
rear-side orbital overlap, inversion at the migrating centre is expected.[1d] This

[178] J. A. Berson and G. L. Nelson, *J. Amer. Chem. Soc.*, 1967, **89**, 5503 and refs. therein.

(CVIII) (CIX)
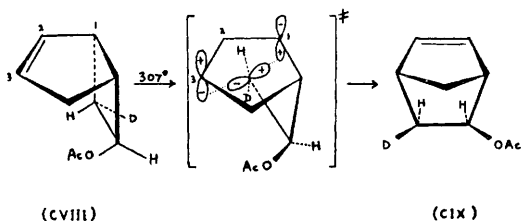
(70)

expectation is realised in reaction (70). The size of the groups attached to the migrating atom are probably of critical importance because of their steric interaction with the allyl framework.

Photochemical [1, 3] *shifts* (*suprafacial*). Of the photochemical [1, 3] shifts that have been reported, a few appear to involve the concerted suprafacial migrations of σ-type centres. The most clear-cut example is provided by the sequence

(CX) (CXI)
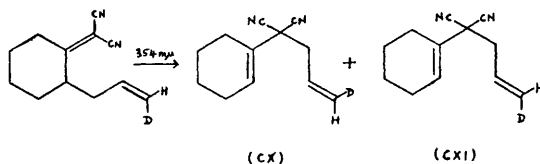
(71)

(71). The *cis–trans* equilibration of the migrating allyl group seems to be an integral part of the rearrangement, since neither the starting material nor (CX) were isomerised under the reaction conditions.[179]

The photochemical conversions of verbenone into chrysanthenone,[180] bullvalene into (CXII),[181] and (CXIII) into (CXIV)[182] might likewise occur by concerted suprafacial shifts. The cobalt-catalysed conversion of allylbenzene into *trans*-propenylbenzene[183] has been suggested[30] as an example of a suprafacial [1, 3] shift which occurs thermally because of the electronic involvement of the metal atom. The formation of 2-phenylcycloheptatriene from the irradiation of the 7-phenyl isomer[184] could involve a [1, 3] hydrogen shift. The alternative possibility of two successive [1, 7] shifts seems more probable, although 1-phenylcycloheptatriene is not isolated from the reaction mixture, since the maximum linear conjugation of the framework radical seems to be generally preferred.

[179] R. F. C. Brown, R. C. Cookson, and J. Hudec, *Chem. Comm.*, 1967, 823.
[180] J. J. Hurst and G. H. Whitham, *J. Chem. Soc.*, 1960, 2864.
[181] M. Jones, *J. Amer. Chem. Soc.*, 1967, **89**, 4236; see also R. N. Warrener and J. B. Bremner, *Rev. Pure Appl. Chem.*, 1966, **16**, 117.
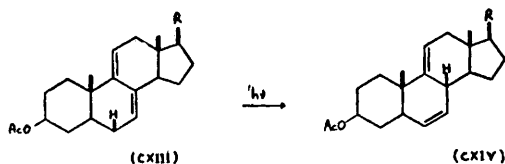[182] W. G. Dauben and W. T. Wipke, *Pure Appl. Chem.*, 1964, **9**, 539.
[183] L. Roos and M. Orchin, *J. Amer. Chem. Soc.*, 1965, **87**, 5502.
[184] A. P. Ter Borg and H. Kloosterziel, *Rec. Trav. chim.*, 1965, **84**, 241.

(CXII)

(72)

(CXIII)   **(CXIV)**

(73)

Thermal [1, 5] *shifts (suprafacial)*. There are many examples of thermal [1, 5] shifts of hydrogen, particularly for ring systems, and the concerted suprafacial pathway is beyond doubt for the migration of this atom. Considerably less is known about the migratory aptitude of other atoms and groups.

Much of the earlier work on dienyl and homodienyl hydrogen shifts both in acyclic (74) and cyclic (75) systems has been the subject of an excellent and concise review.[185] The thermolysis of 3,4-epoxycyclo-octene and of 3,4-epoxy-cycloheptene yields respectively *cis,cis*-3-oxa-1,4-cyclononadiene and *cis,cis*-3-oxa-1,4-cyclo-octadiene. These reactions are analogous to the homodienyl


(74)

$n = 0—5$
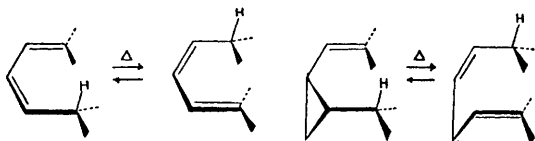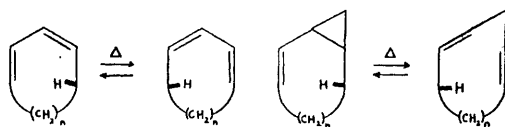
(75)

[1, 5] hydrogen shifts.[186] The π-bonds of carbonyl groups also appear to be capable of participating in homodienyl hydrogen shifts, for example (76).[187]

[185] D. S. Glass, R. S. Boikess, and S. Winstein, *Tetrahedron Letters*, 1966, 999; see also W. R. Roth and J. König, *Annalen*, 1966, **699**, 24.
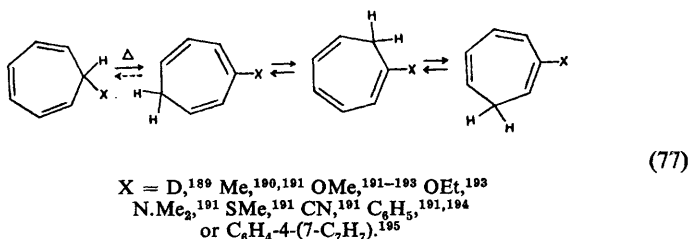[186] J. K. Crandall and R. J. Watkins, *Tetrahedron Letters*, 1967, 1717.
[187] R. M. Roberts and R. G. Landolt, *J. Amer. Chem. Soc.*, 1965, **87**, 2281.

The migration of a hydrogen atom specifically from the *cis*-methyl group has been demonstrated by a deuterium-labelling experiment.[188]

(76)

$$Me.CO.CH_2.CH_2.C(Me) = CH_2$$
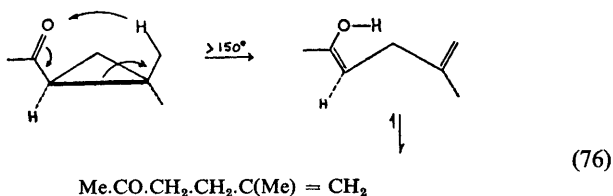
The migration of hydrogen atoms in the thermal reactions of 7-substituted cycloheptatrienes occur by way of [1, 5] shifts although superficially the [1, 7] and [1, 3] pathways also seem possible. The [1, 5] suprafacial migrations, which occur as predicted by the Woodward–Hoffmann theory, are summarised in reaction (77).[189–195]

(77)

X = D,[189] Me,[190,191] OMe,[191–193] OEt,[193]
N.Me$_2$,[191] SMe,[191] CN,[191] C_6H_5,[191,194]
or C_6H_4-4-(7-C_7H_7).[195]

Few examples of the [1, 5] migrations of groups other than hydrogen have been reported. The definitive cases are again for medium-size ring systems. Upon heating to 300° (gas phase) 3,7,7-trimethylcycloheptatriene is equilibrated with the 1,7,7- and 2,7,7-isomers. Although no experimental basis is available for deciding whether the interconversions proceed through biradical or concerted [1, 5] shifts, the latter can be rationalised by the scheme (78),[196] which is also in accord with the results of deuterium-labelling experiments. However, 7,7-dicyanonorcaradiene is isomerised above 100° first to 4,7-dicyanocyclo-heptatriene, and thence to 1,4- and to 1,5-dicyanocycloheptatriene. A series of concerted [1, 5] shifts (79) appears to afford the most reasonable interpretation of these observations.[86] The apparently different behaviour of a methyl sub-

[188] R. M. Roberts, R. N. Greene, R. N. Landolt, and E. W. Heyer, *J. Amer. Chem. Soc.*, 1965, **87**, 2282.
[189] A. P. Ter Borg, H. Kloosterziel, and N. Van Meurs, *Proc. Chem. Soc.*, 1962, 359; *Rec. Trav. chim.*, 1963, **82**, 717.
[190] K. W. Egger, *J. Amer. Chem. Soc.*, 1967, **89**, 3688.
[191] A. P. Ter Borg, E. Razenberg, and H. Kloosterziel, *Rec. Trav. chim.*, 1965, **84**, 1230.
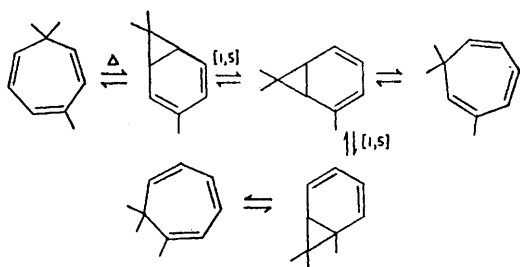[192] E. Weth and A. S. Dreiding, *Proc. Chem. Soc.*, 1964, 59.
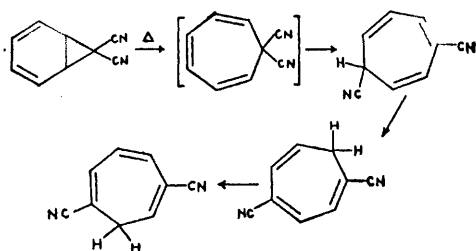[193] T. Nozoe and K. Takahashi, *Bull. Chem. Soc. Japan*, 1965, **38**, 665.
[194] A. P. Ter Borg and H. Kloosterziel, *Rec. Trav. chim.*, 1965, **84**, 245; see also ref. 81.
[195] R. W. Murray and M. L. Kaplan, *J. Amer. Chem. Soc.*, 1966, **88**, 3527.
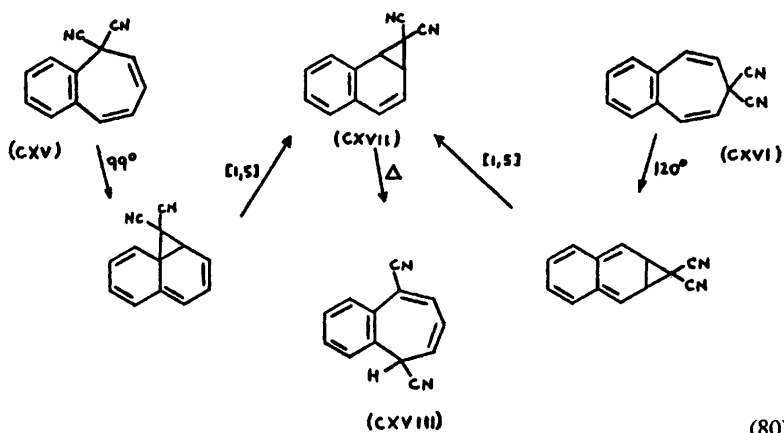[196] J. A. Berson and M. R. Willcott, *J. Amer. Chem. Soc.*, 1966, **88**, 2494.

(78)

(79)

stituent and a cyano-substituent [*e.g.*, (78) *versus* (79)] may be due to the smaller steric requirement of the linear nitrile group, but this cannot be the complete answer since (CXV) and (CXVI) are isomerised to the norcaradiene (CXVII). A scheme (80), analogous to (78), appears to be operative.[86] Likewise the methyl-7,7-dicyanonorcaradienes are thermally isomerised by this circulatory mechanism.[197] Further heating of (CXVII) produces (CXVIII), the [1, 5] CN-shift product.[86]


(80)

[197] J. A. Berson, P. W. Grubb, R. A. Clark, D. R. Hartter, and M. R. Willcott, *J. Amer. Chem. Soc.*, 1967, **89**, 4076.

Atoms other than carbon should be able to migrate with reasonable facility.[185] The ready thermal isomerisations of the phosphine (CXIX)[198] and the aminopentadiene (CXX)[199] are examples of the possible extension of these processes.

(CXIX) $\xrightarrow{70°}$

(81)

(CXX)

$\xrightarrow{90°}$

(82)
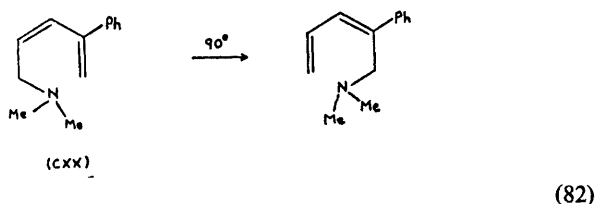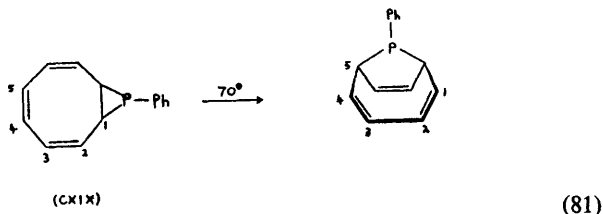
Photochemical [1, 5] *shifts (antarafacial)*. In accord with the predicted antarafacial migration, there appears to be no recorded example of [1, 5] shifts in ring systems where the antarafacial process is clearly impossible. The alternative suprafacial migration of groups which can utilise a low-lying π-orbital also appears to be unknown. In the irradiation of some acyclic 1,3-dienes, products of [1, 5] shifts are occasionally obtained. Other photochemical processes (*e.g.*, ring closure to cyclobutenes), however, usually afford the major reaction pathway. Thus, 2-methyl-*trans*-1,3-pentadiene upon irradiation yields (besides the *cis*-isomer of the starting material) 4-methyl-1,3-pentadiene among other products. Likewise 1-cyclohexyl-1,3-butadiene (*cis*- and *trans*-isomers) is converted into (CXXI; *cis* and *trans*).[45b]


(CXXI)
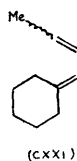
Thermal [1, 7] *shifts (antarafacial)*. There appears to be no known example of a thermally initiated [1, 7] shift in cyclic systems, even for atoms which could migrate by the suprafacial pathway by using a π-type orbital. The [1, 7] migration of hydrogen atoms in the thermal reactions of acyclic hepta-1,3,5-trienes has been known for some time, but the systems studied are very similar to one

[198] T. J. Katz, C. R. Nicholson, and C. A. Reilly, *J. Amer. Chem. Soc.*, 1966, **88**, 3832.
[199] H.-W. Bersch and D. Schon, *Tetrahedron Letters*, 1966, 1141.

another. Perhaps the best known of these reactions are the thermal equilibrations (83) of vitamin D_2 and precalciferol,[76] and of calciferol–precalciferol analogues.[200] The compound (CXXII), which is obtained by irradiating methyl-

(83)

(cxxii)

(84)
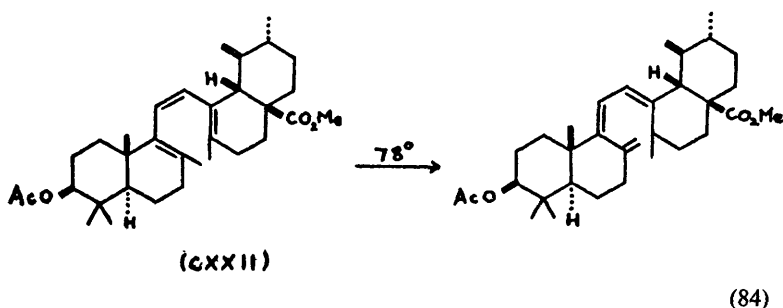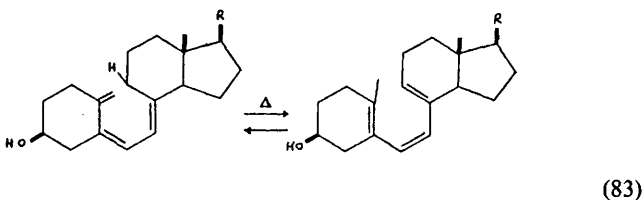
dehydroursolate acetate, is rearranged by heat (84) in a manner analogous to reaction (83).[100] The [1, 7] antarafacial migration of hydrogen atoms reasonably accounts for these observations. In these molecules the heptatrienyl unit must adopt a spiral conformation in the transition state (CXXIII), a geometrical disposition of groups which is admirably suited to the antarafacial hydrogen shift.
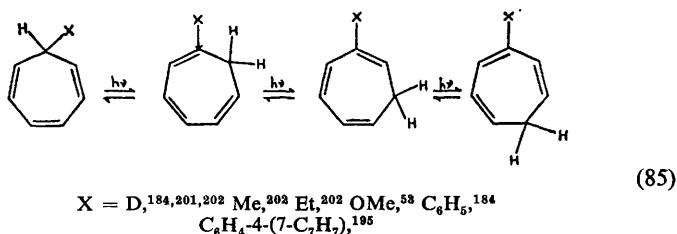

(cxxiii)
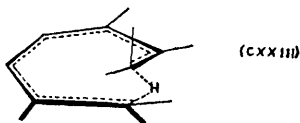
Photochemical [1, 7] *shifts (suprafacial)*. The photochemical excitation of cyclo-heptatrienes furnishes compounds which result from the [1, 7] migration of a substituent group located at C(7). Most usually this group is a hydrogen atom. These [1, 7] hydrogen shifts,[53,184,195,201,202] which are summarised in (85), undoubtedly proceed by the suprafacial pathway because of the presence of the ring system. The distribution of the products depends on the nature of the

[200] J. L. M. A. Schlatmann, J. Pot, and E. Havinga, *Rec. Trav. chim.*, 1964, **83**, 1173.
[201] W. von E. Doering and P. P. Gaspar, *J. Amer. Chem. Soc.*, 1963, **85**, 3043.
[202] R. Roth, *Angew. Chem. Internat. Edn.*, 1963, **2**, 688.

$$X = D,^{184,201,202} Me,^{202} Et,^{202} OMe,^{53} C_6H_5,^{184}$$
$$C_6H_4\text{-}4\text{-}(7\text{-}C_7H_7),^{195}$$

(85)

group X, and not all of the isomeric cycloheptatrienes are formed in each of the above cases. For example, with the 7-phenyl compound as starting material, only 2-phenylcycloheptatriene is isolated. This compound could arise by two consecutive [1, 7] H-shifts, or by a [1, 3] H-shift. In these migrations, the framework radical usually assumes the maximum degree of linear conjugation[1d] so that the [1, 3] shift seems less probable.

The photochemically initiated [1, 7] shifts of hydrogen atoms in 1-substituted cycloheptatrienes have also been investigated. The proportions in which the isomeric products are formed is again dependent upon the nature of the 1-substituent in the starting material.[54] These reactions are essentially the final two stages of (85). The migration of methyl groups may be observed in suitable cases, for example (86)[203] and (87),[204a] but data on other types of [1, 7] migration

(86)

(87)
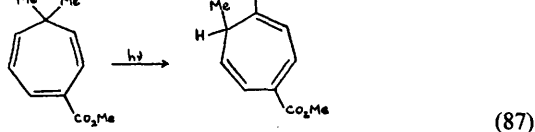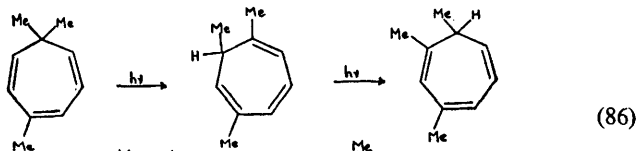
are lacking.

The successes of the rules (which are based on an acyclic model) for cyclic systems is almost fortuitous. During the concerted migration of a group (R) formerly attached to C(n) of a $C_nH_{2n+1}R$ monocycle, the cyclic framework radical (C_nH_{2n+1}) is completely cyclically conjugated and its electronic energy states are distinctly different from those of the analogous acyclic system. However, the symmetry restrictions based on the more realistic cyclic model are in good agreement with those formulated for the less satisfactory acyclic model except that in the cycloheptatriene system [1, 3], [1, 5], and [1, 7] shifts are permitted under photochemical control.[204b] Experiment does not allow a choice

[203] L. B. Jones and V. K. Jones, *J. Amer. Chem. Soc.*, 1967, **89**, 1880 [the conclusions of footnote (9) of this paper are incorrect].
[204] (a) O. L. Chapman and S. L. Smith, *J. Org. Chem.*, 1962, **27**, 2291 ; (b) A. G. Anastassiou, *Chem. Comm.*, 1968, 15.

between the two predictions at present since only the photochemical [1, 7] shifts have been observed. In a molecule such as 3-t-butylcycloheptatriene, however, a single photochemical [1, 5] hydrogen shift would alleviate a considerable amount of steric strain, and a study of such a system might be worthwhile in the above connexion.

Other [1, *j*] *shifts.* Migrations of order higher than [1, 7] are likely to be difficult, even in ring systems, because of the need for near planarity (*i.e.*, substantial through-conjugation) of the framework radical. Recently, however, the thermal sigmatropic migrations of 1-substituents of 1-substituted (*i.e.*, CH_3) and 1,19-disubstituted (*i.e.*, CO_2Et) nickel tetradehydrocorrins have been described. The migrations may be formally regarded as [1, 17] (for CH_3) and [1, 5] or [1, 17] (for CO_2Et) shifts respectively. Preliminary Hückel calculations indicate[205] that the highest occupied orbital of the metal-free macrocycle has the correct symmetry for the suprafacial migration from (C1) to C(2).

B. Sigmatropic Rearrangements of Order [*i, j*].—Uncatalysed intramolecular sigmatropic changes of order [*i, j*] have also been considered by Woodward and Hoffmann in a further communication.[1e] Their theoretical treatment assumes that these systems can be likened to the intimate interaction of a pair of polyenyl radicals possessing respectively *i* and *j* conjugated atoms. A topological distinction on both framework radicals is thus possible, and the main theoretical conclusions can be summarised as in Table 3 (*s* = suprafacial, *a* = antarafacial interactions).[2]

Table 3

[*i, j*]	Thermal	Photochemical
[3, 3]	*s–s*	*s–a*
[3, 5]	*s–a*	*s–s*
[5, 5]	*s–s*	*s–a*

The thermal [3, 3] migrations are more widely known as the Cope and Claisen rearrangements. Both reactions are of great theoretical and preparative importance and accordingly the amount of experimental work which has been,[206,207] and continues to be,[208] carried out on [3, 3] shifts is enormous. Of particular

[205] R. Grigg, A. W. Johnson, K. Richardson, and K. W. Shelton, *Chem. Comm.*, 1967, 1192.
[206] S. J. Rhoads, in "Molecular Rearrangements", ed. P. de Mayo, Interscience, New York, 1963, Part I, p. 655.
[207] E. Vogel, *Angew. Chem. Internat. Edn.*, 1963, **2**, 1; W. von E. Doering and W. R. Roth, *ibid.*, p. 115.
[208] For example, see B. Miller, *J. Amer. Chem. Soc.*, 1965, **87**, 5515; S. F. Reed, *J. Org. Chem.*, 1965, **30**, 1663; E. Vogel, R. Erb, G. Lenz, and A. A. Bothner-By, *Annalen*, 1965, **682**, 1; H. A. Staab and F. Vögtle, *Chem. Ber.*, 1965, **98**, 2681, 2691; H. A. Staab and C. Wünsche, *ibid.*, p. 3479; A. Viola, E. J. Iorio, K. K. Chen, G. M. Glover, U. Nayak, and P. Kocienski, *J. Amer. Chem. Soc.*, 1967, **89**, 3462; W. von E. Doering and W. R. Roth, *Tetrahedron*, 1963, **19**, 715; G. Schröder, *Angew. Chem. Internat. Edn.*, 1963, **2**, 481; A. F. Thomas, *Chem. Comm.*, 1967, 947; L. A. Paquette, T. J. Barton, and E. B. Whipple, *J. Amer. Chem. Soc.*, 1967, **89**, 5481; G. M. Blackburn, W. D. Ollis, J. D. Plackett, C. Smith, and I. O. Sutherland, *Chem. Comm.*, 1968, 186.

interest within the framework of the Woodward–Hoffmann theory are those experimental observations which allow a direct test of the theoretical predictions. One such prediction is that in thermally controlled [3, 3] sigmatropic rearrangements there should be a distinct preference for a chair-like transition state.[1e] Some thirteen years previously Doering and Roth had recorded such a preference for the particular transition-state geometry represented by (CXXIV) from the results of their classical work on the thermolysis of *meso-* and (±)-3,4-dimethylhexa-1,5-dienes.[207,209] The high stereospecificity of [3, 3] migrations has been further confirmed by work on the thermal reactions of optically active *N*-allylamines [amino-Claisen rearrangement (89)][210] and of optically active hepta-1,5-dienes [Cope rearrangement (90)].[211] In each case two products are formed which possess opposite configurations not only at the double bonds but also at the centres of asymmetry. The optical purity of each product is very
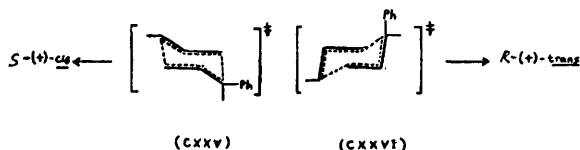

(CXXIV)
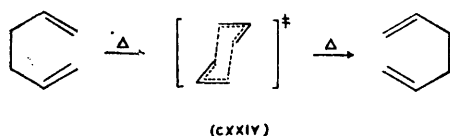
(88)
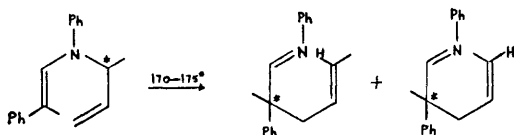
(89)
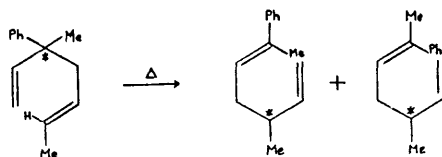
(90)

high. These observations are only consistent with four-centre chair-like transition states [*e.g.*, (CXXV) and (CXXVI) for reaction (90)][211] for the migration, and not with the alternative six-centre boat conformations.


(CXXV)   (CXXVI)

[209] W. von E. Doering and W. R. Roth, *Tetrahedron*, 1962, **18**, 67.
[210] R. K. Hill and N. W. Gilman. *Tetrahedron Letters*, 1967, 1421.
[211] R. K. Hill and N. W. Gilman, *Chem. Comm.*, 1967, 619.

Alternative theoretical treatments of the observed preference for the four-centre transition state conformation in concerted thermal [3, 3] migrations have been discussed.[3b,212]

The photochemical [3, 3] migrations should proceed by way of a suprafacial-antarafacial interaction of the two allyl systems in the transition state, a type of interaction which is not favourable. There is no clear-cut example of a concerted photochemical [3, 3] migration.[213] However, [3, 5] shifts should occur with reasonable facility under photochemical control, and it seems likely that a migration of this type has been observed. Upon irradiation, allyl 2,6-dimethylphenyl ether (isotopically labelled mainly at the position indicated *) is partially converted into 2,6-dimethyl-4-(prop-3-enyl)phenol (91). The radioactive tracer is approximately equally distributed between C(1) and C(3) of the allyl system in (CXXVII).[214] This result can be explained in terms of two competing migrations; a two-stage thermal migration (*i.e.*, *para*-Claisen rearrangement) and a one-step concerted [3, 5] shift, passing through an eight-membered transition state, under photochemical control. If the two mechanisms are of about equal importance, a 50% scrambling of the label would be expected. A thermal [3, 5] rearrange-
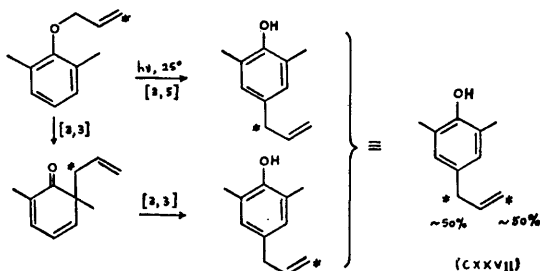
(91)

ment in a related system[215] seems less likely to involve a one-step concerted reaction passing through an eight-membered transition state.[1d,206]

Very recently a [5, 5] concerted migration (92) has been described,[216] although any preference for a chair-like four-centre transition state[1e] has yet to be detected.

5 Miscellaneous Reactions

The orbital symmetry arguments have been extended to rationalise and predict virtually every concerted organic reaction.[1,2] Examples include sigmatropic changes within ionic species,[1d,2,217] valence tautomerisms of cyclic conjugated

[212] M. Simonetta and G. Favini, *Tetrahedron Letters*, 1966, 4835; M. Simonetta, G. Favini, C. Mariani and P. Gramoccioni, *J. Amer. Chem. Soc.*, 1968, 90, 1280.
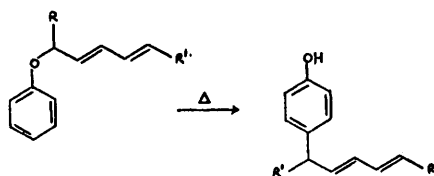[213] See, for example, H. N. Subba Rao, N. P. Damordaran, and S. Dev, *Tetrahedron Letters*, 1967, 227.
[214] K. Schmid and H. Schmid, *Helv. Chim. Acta*, 1953, 36, 687.
[215] P. Fahrni and H. Schmid, *Helv. Chim. Acta*, 1959, 42, 1102.
[216] Gy. Fráter and H. Schmid, *Helv. Chim. Acta*, 1968, 51, 190.
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(92)

(CXXVIII) (a) R = R' = H; (b) R = H, R' = Me; (c) R = Me, R' = H.

olefins,[2,59] double terminal additions of acetylene to polyenes,[2,102] and general-ised Cope rearrangements.[2,102] Because of the lack of experimental verification of the predictions in many of these cases, it would be premature to consider these systems here.

6 Conclusions

The agreement between experimental observation and the predictions of Wood-ward and Hoffmann's elegant theory are extremely satisfactory. The reper-cussions of orbital symmetry arguments have already brought marked changes in the philosophy of the molecular orbital method.[2,218] The rules (which one must remember are permissive for a particular concerted reaction, but not obligatory) will undoubtedly be of great assistance in certain areas of preparative organic chemistry.

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