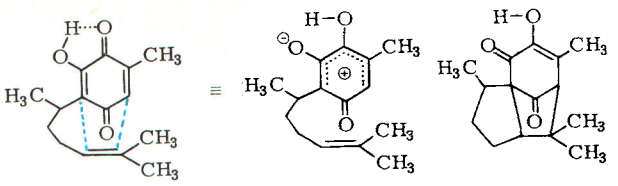
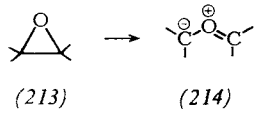


(209) (210)

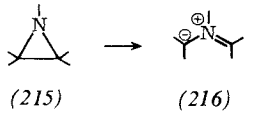
As yet, no simple instances of class C ionic [4+2] cycloadditions have been discovered. However, a very important and numerous group of reactions – the 1,3-dipolar additions [103] – may be placed in this class, since the 1,3-dipolar substances which participate in cycloaddition reactions, although formally neutral molecules, generally function as three-orbital 4π-electron species. *Huisgen*, whose own magnificent researches have transformed 1,3-dipolar addition from an obscure phenomenon, exemplified only by a few curiosities, into a major reaction-type, has presented excellent surveys of the field [103], and has analyzed the process in terms of orbital symmetry conservation [104]. Consequently, it is only necessary here to summarize briefly the major fundamental factors, and to allude to a few special points. The great majority of known participants in 1,3-dipolar addition reactions are isoelectronic either with ozone *(211)* or with nitrous oxide *(212)*, and unambiguously contain a three-orbital system occupied by four π electrons.

(211) (212)

Another class of reactants is represented by labile molecules which undergo ready transformation into species containing the requisite 4-electron system, *e.g.* the carbonyl ylides *(214)* and the azomethine ylides *(216)* are produced by electrocyclic transformation of ethylene oxides *(213)* and ethylene imines *(215)*, substituted in such wise as to facilitate ring cleavage; the symmetry-determined conrotatory course of these antecedent processes has already been discussed above (*cf.* Section 5).

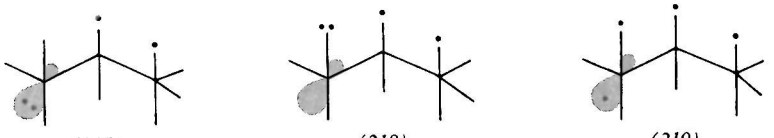


(213) (214)



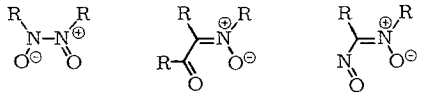
(215) (216)

The situation in respect to the possibility of the participation, in concerted cycloaddition reactions, of fugitive species such as vinylcarbene and its isoelectronic analogues, presents interesting ambiguities. Such molecules may exist in three forms, differing in the number of π electrons occupying the allyl orbital. The first, *(217)*, containing two electrons in the allyl system, may be expected to combine with dienes in a [2+4] process, but independent reaction as a simple substituted carbene could supervene. The second, *(218)*, with four electrons in the allyl system, should undergo normal concerted combination with 2 π-electron molecules, while the third, *(219)*, is an analogue of triplet carbene. These systems have not been extensively studied; it may be expected that their electronic structures, and consequently the courses of their reactions will vary as the backbone atoms, and attached substituents, are varied.



(217) (218) (219)

Brief mention may be made of the possibility of analogues of 1,3-dipolar additions, in which larger numbers of electrons are incorporated in the π system of the dipolar component. As speculative examples, the *cis* form *(220)* of a dimeric nitroso compound, the α-ketonitrones *(221)*, and the α-nitrosonitrones *(222)*, all contain 6 π-electron systems, and concerted combination with dienes is symmetry-allowed.



(220) (221) (222)

A special word of caution should be added in relation to 1,3-dipolar additions. There may well be instances of such reactions in which the complementary polar character of the reactants is sufficiently extreme as to favor two-step combination, proceeding through a relatively stable dipolar intermediate.

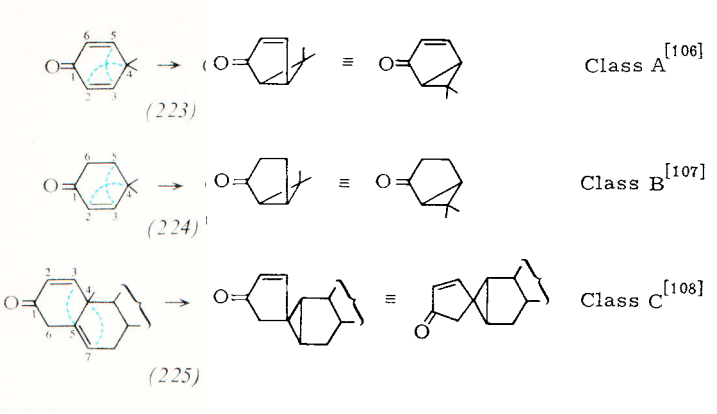
6.2. [2+2] Cycloadditions in the Photochemistry of the Cyclohexadienones and Cyclohexenones

Following the pioneering work of *Barton*, *Jeger*, and their co-workers, the beautiful complexity of the photochemistry of cyclohexadienones and cyclohexenones has been most ably explored by *Chapman*, *Schaffner*, *Schuster*, *Zimmerman*, and their collaborators [105].

[103] *R. Huisgen*, Angew. Chem. *75*, 604 (1963); Angew. Chem. internat. Edit. *2*, 565 (1963); *R. Huisgen*, *R. Grashey*, and *J. Sauer*, in *S. Patai:* The Chemistry of Alkenes. Interscience, New York 1964, p. 739; *R. Huisgen*, Helv. chim. Acta *50*, 2421 (1967).

[104] *A. Eckell*, *R. Huisgen*, *R. Sustmann*, *G. Wallbillich*, *D. Grashey*, and *E. Spindler*, Chem. Ber. *100*, 2192 (1967).

[105] Two recent reviews serve as excellent guides to the elegant structural work accomplished. (a) *K. Schaffner*, Advances in Photochemistry *4*, 81 (1966); (b) *P. J. Kropp*, Organic Photochemistry *1*, 1 (1967).



The primary isomerization processes which have been noted are of three types *(223)–(225)*.

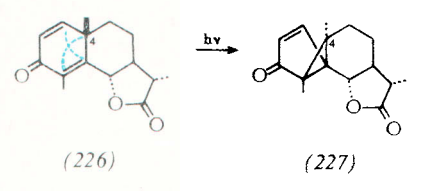
It seems probable that all, and has been established that some, of these cases involve reactions proceeding through n,π* triplet states. It has also been clearly established that the quantum efficiency of the processes varies over a very wide range[109]. Detailed mechanisms have been proposed for these reactions[110]; the most elaborate and ingenious of these mechanisms is that suggested by *Zimmerman*[111].

We would like to examine the stereochemical constraints imposed by conservation of orbital symmetry on these transformations. These constraints are operative only if the reactions are concerted. We are aware of the elegant physical measurements which have been interpreted as supporting the proposed non-concerted mechanisms. But we regard it as worth while to stipulate the stereochemical imperatives associated with concerted paths from the starting materials to the observed products.

Formally, all of the reactions are $[\sigma 2+\pi 2]$ cycloadditions. If they are concerted changes within excited states, such cycloadditions must be $[\sigma 2_s+\pi 2_s]$ or $[\sigma 2_a+\pi 2_a]$ reactions.

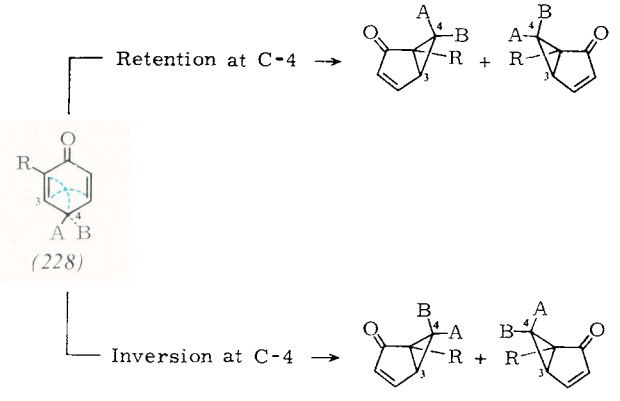
In classes A and B suprafacial participation of double bond 2,3 is a stereochemical impossibility, since it leads to *trans* fused three- and five-membered rings. Consequently, these reactions must follow the $[\sigma 2_a+\pi 2_a]$ course, which requires antarafacial addition at double bond 2,3, and inversion at C-4. In class C the special constraint present in classes A and B is absent. Both $[\sigma 2_a+\pi 2_a]$ and $[\sigma 2_s+\pi 2_s]$ processes are feasible.

Antara addition at the double bond and inversion at the migrating saturated carbon atom is of course precisely what occurs in the classic conversion of santonin



(226) into lumisantonin *(227)*[112]. Unfortunately, in this case the alternative symmetry-forbidden change, taking place with retention at C-4, would lead to a sterically unlikely *trans* ring fusion; consequently, it might be argued that the observed path, though symmetry-allowed, would in any event be imposed by the geometry of the system.

The simplest labeling of the parent cyclohexadienone which would endow it with a center of chirality would also allow in principle a resolution of this question. Consider the consequences of retention or inversion at C-4 on such a chiral cyclohexadienone *(228)*[113]. Inversion or retention at C-4 can each be performed in



two distinct ways, depending on whether the addition at C-3 is on top or bottom. If A and B are different substituents these pathways become distinct, each with its own steric factors. It is thus likely that even a stereospecific process will yield two products in differing proportions. The products of inversion are diastereomeric, and enantiomeric to the products of retention. The actual course followed in the rearrangement of a simple chiral cyclohexadienone has not yet been determined,

[106] *D. H. R. Barton, J. McGhie,* and *R. Rosenberger*, J. chem. Soc. *1961*, 1215; *D. H. R. Barton, P. de Mayo,* and *M. Shafiq, ibid. 1958*, 140, 3314; *D. Arigoni, H. Bosshard, H. Bruderer, G. Büchi, O. Jeger,* and *L. J. Krebaum*, Helv. chim. Acta *40*, 1732 (1957) and other papers referred to in ref. [105].

[107] *W. W. Kwie, B. A. Shoulders,* and *P. D. Gardner*, J. Amer. chem. Soc. *84*, 2268 (1962); *O. L. Chapman, T. A. Rettig, A. A. Griswold, A. I. Dutton,* and *P. Fitton*, Tetrahedron Letters *1963*, 2049; *B. Nann, D. Gravel, R. Schorta, H. Wehrli, K. Schaffner,* and *O. Jeger*, Helv. chim. Acta *46*, 2473 (1963) and other papers referred to in ref. [105].

[108] *B. Nann, D. Gravel, R. Schorta, H. Wehrli, K. Schaffner,* and *O. Jeger*, Helv. chim. Acta *46*, 2473 (1963); *B. Nann, H. Wehrli, K. Schaffner,* and *O. Jeger, ibid. 48*, 1680 (1965).

[109] *H. E. Zimmerman, R. G. Lewis, J. J. McCullough, A. Padwa, S. Staley,* and *M. Semmelhack*, J. Amer. chem. Soc. *88*, 159 (1966); *O. L. Chapman, J. B. Sieja,* and *W. J. Welstead, jr., ibid. 88*, 161 (1966).

[110] *H. E. Zimmerman*, Advances in Photochemistry *1*, 183 (1963); *O. L. Chapman, ibid. 1*, 323 (1963).

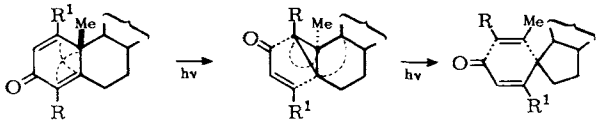
[111] *H. E. Zimmerman*, 17th National Organic Symposium of the American Chemical Society, Bloomington, Indiana, 1960, Abstracts, p. 31; *H. E. Zimmerman* and *D. I. Schuster*, J. Amer. chem. Soc. *83*, 4486 (1961); *84*, 4527 (1962); *H. E. Zimmerman*, Tetrahedron *19*, Supplement 2, 393 (1963).

[112] *D. H. R. Barton, P. de Mayo,* and *M. Shafiq*, J. chem. Soc. *1958*, 140; *D. Arigoni, M. Bosshard, H. Bruderer, G. Büchi, O. Jeger,* and *L. J. Krebaum*, Helv. chim. Acta *40*, 1732 (1957); *W. Cocker, K. Crowley, J. T. Edward, T. B. H. McMurry,* and *E. R. Stuart*, J. chem. Soc. *1957*, 3416; *D. H. R. Barton* and *P. T. Gilham*, J. chem. Soc. *1960*, 4596.

[113] Only the consequences of an addition on the double bond next to R are sketched. Of course the addition on the opposite side is feasible, and will double the number of possible products.

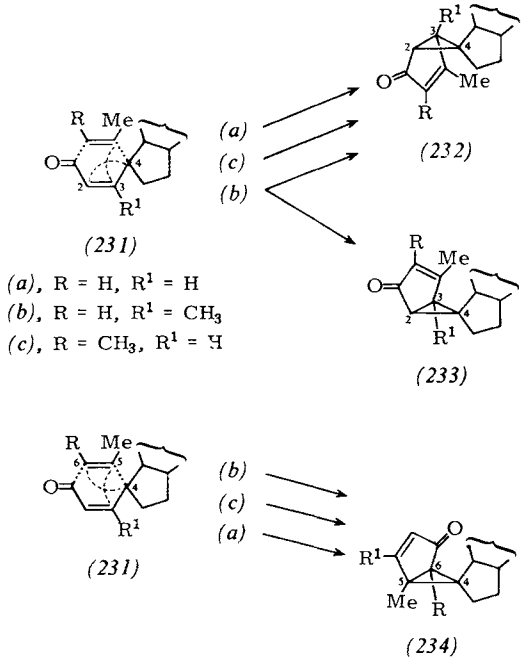
but is being studied by *Schuster*[114] who has independently recognized that the matter is one of great interest.

The versatile field of steroid derivatives appears already to have provided verifications of our predictions. The remarkably rich photochemistry of 1-dehydrotestosterone acetate and its methyl derivatives[115] begins with the now familiar conversion of a 2,5-cyclohexadienone *(229)* into a bicyclo[3.1.0]hexenone *(230)*, and thence to a new cyclohexadienone *(231)* of assigned



(229) *(230)* *(231)*

stereochemistry. On further photolysis *(231)* furnishes two or three isomers, depending on the pattern of substitution. The ingeniously assigned[115] structures of the products are shown in formulae *(232)–(234)*.



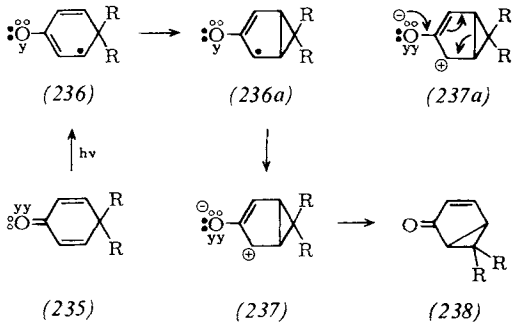
(231)

(a), R = H, R^1 = H
(b), R = H, R^1 = CH_3
(c), R = CH_3, R^1 = H

(232) *(233)* *(234)*

The molecules *(232)*, *(233)*, and *(234)* are all products of $[\pi 2_a + \sigma 2_a]$ processes, precisely as predicted from orbital symmetry considerations for concerted changes; it is especially to be noted that inversion must occur at C-4 during each of the photoisomerizations. For the substitution patterns *(a)* and *(c)* only one product *(232)* of the two which might result from symmetry-allowed changes involving the 2,3 double bond is observed. Similarly, only *(234)* is produced from *(a)* and *(c)* when the 5,6 double bond is implicated. In the case of *(b)*, three of the four possible products of symmetry-allowed processes have been isolated. Not one of the four products which might result from symmetry-forbidden or non-stereospecific processes has been found.

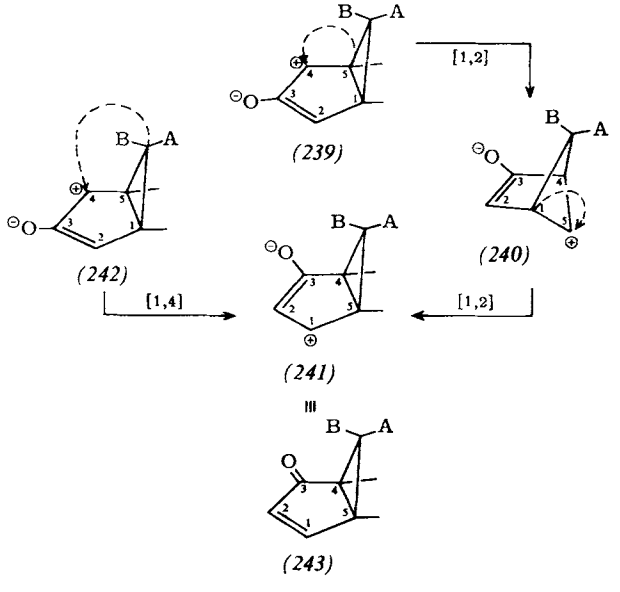
Unfortunately, the Zimmerman mechanism[111] for reactions of class A, illuminated with the insight afforded by orbital symmetry considerations, leads to precisely the same products which must be obtained in a concerted reaction. Formulae *(235)–(238)* show the basic mechanism suggested by *Zimmerman*[111].



(236) *(236a)* *(237a)*

(235) *(237)* *(238)*

The final step, following bond reorganization [*(236)*→*(236a)*] (symmetry-allowed!) and demotion [*(236a)*→*(237)*] is formally a ground-state cyclopropylcarbinyl rearrangement; note that reversion of *(237)* to the original cyclohexadienone *(235)* [*cf.* arrows in *(237a)*] is symmetry-forbidden! There are actually two possibilities for the last step of this sequence. They are best described as [1,2n] sigmatropic shifts (*cf.* Section 7, below). The first process consists of two sequential [1,2] shifts [*(239)*→*(240)*→*(241)* ≡ *(243)*], while the second is a [1,4] rearrangement [*(242)*→*(241)* ≡ *(243)*]. Since [1,2] sigmatropic shifts must



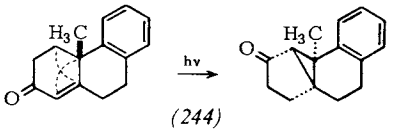
(239) *(240)* *(242)* *(241)* *(243)*

proceed with *retention*, but [1,4] shifts, if forced to be suprafacial, must proceed with *inversion* at the migrating carbon, it follows that the consequences of the two alternatives are stereochemically indistin-

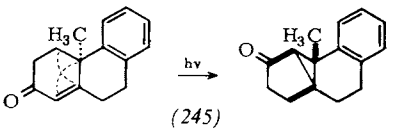
[114] *D. I. Schuster*, personal communication.

[115] *H. Dutler, M. Bosshard*, and *O. Jeger*, Helv. chim. Acta *40*, 494 (1957); *K. Weinberg, E. C. Utzinger, D. Arigoni*, and *O. Jeger*, *ibid. 43*, 236 (1960); *H. Dutler, C. Ganter, H. Ryf, E. C. Utzinger, K. Weinberg, K. Schaffner, D. Arigoni*, and *O. Jeger*, *ibid. 45*, 2346 (1962); *C. Ganter, F. Greuter, D. Kägi, K. Schaffner*, and *O. Jeger*, *ibid. 47*, 627 (1964); *F. Frei, C. Ganter, D. Kägi, K. Kocsis, M. Miljković, A. Siewinski, R. Wenger, K. Schaffner*, and *O. Jeger*, *ibid. 49*, 1049 (1966).

guishable. Thus, for reactions of class A, either a totally concerted mechanism or a stepwise one involving concerted elements leads to the same stereochemical results. While the physical evidence adduced for the chronology proposed by *Zimmerman* is very impressive, we do not regard it as conclusive: either mechanism remains a possibility.

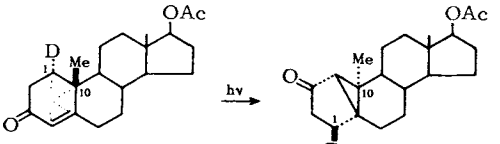


(244)



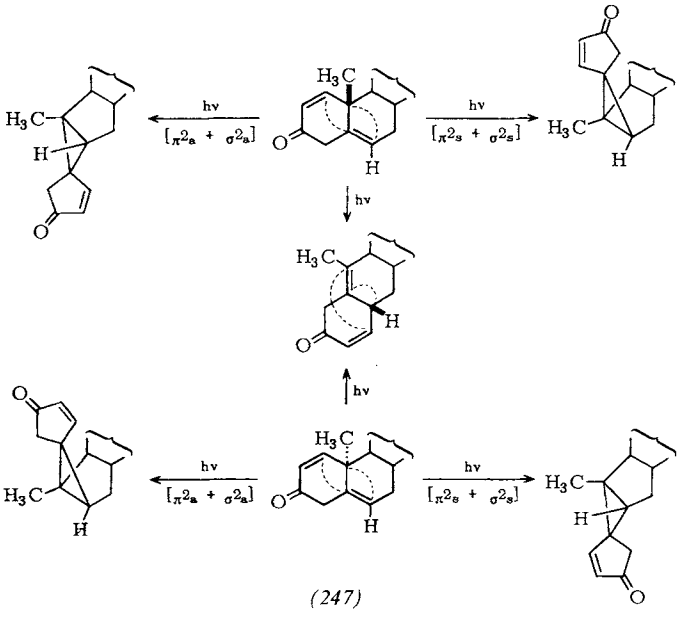
(245)

The photochemical rearrangement of cyclohexenones (the class B reactions) is a highly stereospecific process, and very probably follows a concerted course. Thus, *Chapman* found [116] retention of chirality in the reactions *(244)* and *(245)*.



(246)

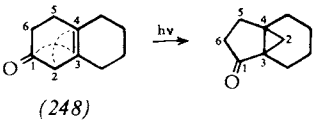
Belluš and *Schaffner* [117] studied the reaction with a very subtle probe; the isomerization of *(246)* proceeds with retention at C-1 and inversion at C-10. The inversion at C-10 is forced by the steric situation, but the retention at C-1 is not, and is clearly inconsistent with a radical fragmentation of the C(1)-C(10) bond.



(247)

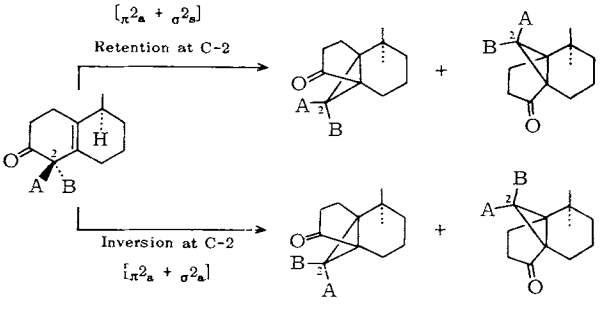
We turn now to reactions of class C. In this case there are no steric restraints operative against either the $[\pi 2_s+\sigma 2_s]$ or the $[\pi 2_a+\sigma 2_a]$ concerted processes. In the beautiful case *(247)* that has been studied [108] just the products predicted for the two allowed cycloadditions are found. But once again avoidance of *trans* fused rings would lead to the very same stereochemical consequences for stepwise processes.

There are two further photochemical transformations of enones which fall into the category of [2+2] cycloadditions. The first of these is an isomerization of a nonconjugated cyclohexenone *(248)* [118].



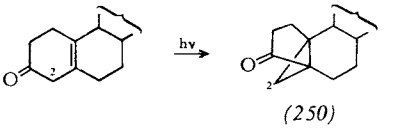
(248)

Formulae *(249)* show the consequences of the stereochemically feasible reactions *antara* on the double bond with options of retention or inversion at C-2.



(249)

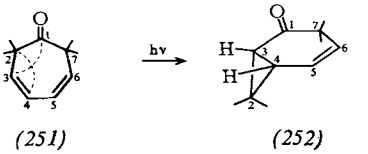
A steroidal derivative of this class has been photolyzed [118]. Of the two distinct possible products, only that one is produced whose cyclopropane ring is α-oriented *(250)*. Since labels are lacking at C-2, the pri-



(250)

mary question of retention or inversion is as yet unanswered. We predict that the reaction will be found to proceed with inversion at C-2. Similar circumstances obtain in the case of a further example [*(251)*→*(252)*] [119].

There appear to be a number of examples of photochemically induced $[\pi 2_a+\sigma 2_a]$ cycloadditions involving



(251) *(252)*

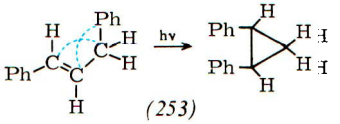
[116] *O. L. Chapman, J. B. Sieja,* and *W. J. Welstead, jr.*, J. Amer. chem. Soc. *88*, 161 (1966).

[117] *D. Belluš, D. R. Kearns,* and *K. Schaffner*, Helv. chim. Acta *52*, 971 (1969).

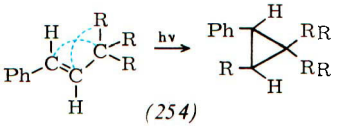
[118] *J. R. Williams* and *H. Ziffer*, Chem. Commun. *1967*, 194, 469; Tetrahedron *24*, 6725 (1968).

[119] *L. A. Paquette, R. F. Eizember,* and *O. Cox*, J. Amer. chem. Soc. *90*, 5153 (1968).

simple olefins and dienes. Thus, *Griffin* [120] observed unusual propylene→cyclopropane cyclizations accompanied by group migrations [*(253)*, *(254)*]. These could well be concerted transformations, but definitive stereochemical information is lacking.

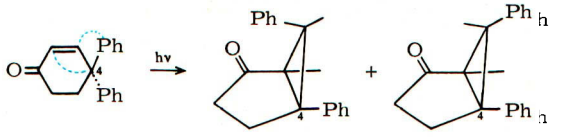


(253)



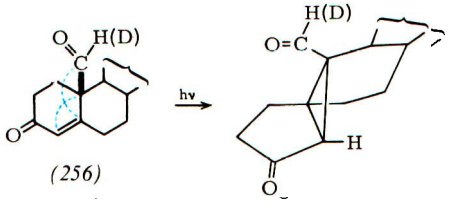
(254)

An instance of this type of reaction in which the stereochemical course has been established is available in the photolysis of 4,4-diphenylcyclohexenone *(255)* [121]. The predominant product is the result of an antarafacial addition on the double bond and inversion at C-4.



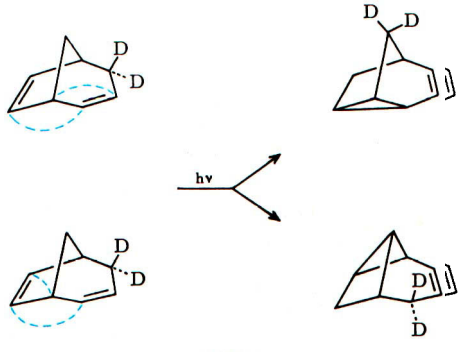
(255) 140 : 1

A probable further example of a $[\sigma 2_a+\pi 2_a]$ reaction has emerged in a recent study of the photolysis of 3,19-dioxo-4-androsten-17β-yl acetate *(256)* [122].



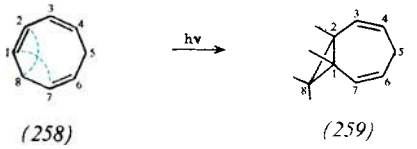
(256)

Still other possible $[\sigma 2_a+\pi 2_a]$ changes, constrained to proceed as such, are available in the case *(257)* studied by *Sauers* [123].

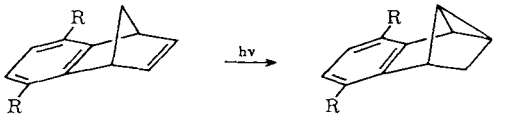


(257)

The formation of *(259)* on photolysis of cyclooctatriene *(258)* is also constrained to follow the $[\pi 2_a+\sigma 2_a]$ course, if concerted; it has been shown that the process occurs without a hydrogen shift [124].

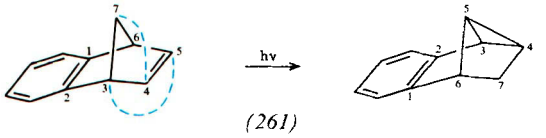


(258) *(259)*

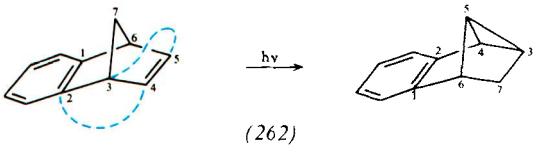


(260)

A related case *(260)* has been observed by *Edman* [125]. A concerted cycloaddition may involve either the σ bond at 3,7 *(261)* or that at 2,3 *(262)*. The concerted



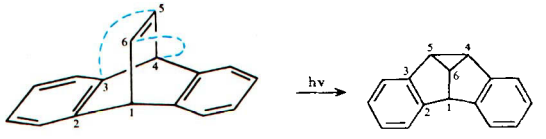
(261)



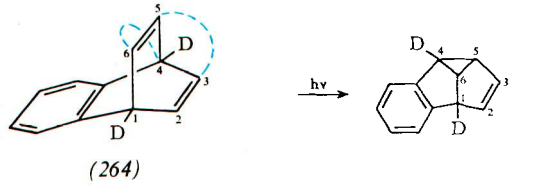
(262)

nature of the reaction could be ascertained using a chiral reactant.

Still other reactions of this type are found in the conversion of a dibenzobicyclo[2.2.2]octatriene *(263)* to a dibenzosemibullvalene [126] and of a labeled benzobicyclo[2.2.2]octatriene *(264)* to a benzosemibullvalene [127]



(263)



(264)

[120] *G. W. Griffin, J. Covell, R. C. Petterson, R. M. Dodson*, and *G. Klose*, J. Amer. chem. Soc. *87*, 1410 (1965); *H. Kristinsson* and *G. W. Griffin, ibid. 88*, 378 (1966).

[121] *H. E. Zimmerman* and *K. G. Hancock*, J. Amer. chem. Soc. *90*, 3749 (1968). See also *H. E. Zimmerman* and *R. L. Morse, ibid. 90*, 954 (1968).

[122] *E. Pfenninger, D. E. Poel, C. Berse, H. Wehrli, K. Schaffner*, and *O. Jeger*, Helv. chim. Acta *51*, 772 (1968).

[123] *R. R. Sauers* and *A. Shurpik*, J. org. Chem. *33*, 799 (1968).

[124] *W. R. Roth* and *B. Peltzer*, Liebigs Ann. Chem. *685*, 56 (1965).

[125] *J. R. Edman*, J. Amer. chem. Soc. *88*, 3454 (1966).

[126] *E. Ciganek*, J. Amer. chem. Soc. *88*, 2882 (1966).

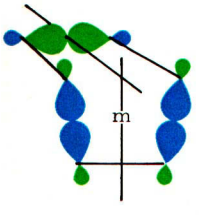
[127] *H. E. Zimmerman, R. S. Givens*, and *R. M. Pagni*, J. Amer. chem. Soc. *90*, 4192 (1968). See also *J. P. N. Brewer* and *H. Heaney*, Chem. Commun. *1967*, 811; *P. W. Rabideau, J. B. Hamilton*, and *L. Friedman*, J. Amer. chem. Soc. *90*, 4465 (1968).

We emphasize that neither of these cases need be concerted; indeed, there is evidence for a stepwise process in the corresponding reaction of the parent barrelene [128].

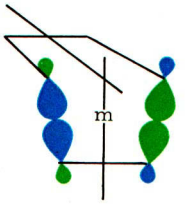
We must now examine the question of how a process shown to proceed through an excited triplet state of a molecule could possibly be concerted. We believe that orbital symmetry relationships dictate to a molecule in an excited state a certain set of motions, leading to reaction, which are facile, and another set of motions which are difficult. There is no necessity to reach the excited state of products. The symmetry-allowed motions are initiated in the excited state of the reactant. In their course they are accompanied by a radiationless transition to the ground-state of the product. While the physical rationale of such a transition is still lacking, the occurrence of such a process presents no more difficulty than does any other radiationless transition.

6.3. The [2+2+2] Cycloaddition Reaction

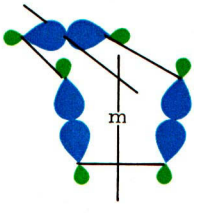
Further useful practice in the application of the principle of orbital symmetry conservation may be gained from a detailed consideration of the [2+2+2] concerted cycloaddition (or cycloreversion) reaction; the exercise is made the more valuable through the emergence from it of some new factors, and through the fact that it sets the stage for comparisons, in the sequel, which deepen our understanding of orbital symmetry conservation as a fundamental extension of our knowledge of the phenomenon of chemical bonding.



(265)

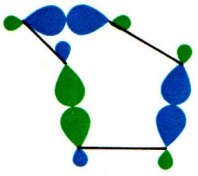


(266)

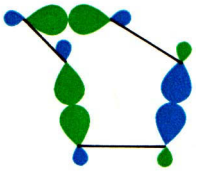


(267)

Let us consider the decomposition of cyclohexane, through a boat-shaped transition state, into three molecules of ethylene. First, we assign six electrons – those involved in the bonds to be broken – in pairs, to the generalized σ orbitals *(265)*, *(266)*, and *(267)* [*cf.* Section 3.1]. Note that the only symmetry element imposed by the geometry of the system is the mirror plane *m*, and that the orbitals shown are, as required, either symmetric or antisymmetric with respect to that element. *It is of especial importance in this case to observe the fundamental principle that unsymmetrical molecular orbitals are not permissible:* thus, the orbital *(268)* is not real, and must be expunged by addition to its equally unreal conjugate *(269)*. It is also worthy of

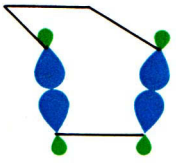


(268)

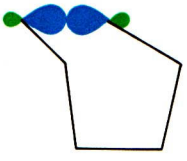


(269)

note that the orbitals *(267)* and *(265)* may be replaced by their sum *(270)* and difference *(271)*, with no change in any conclusion which may be discovered from their use; but in general the most obviously informative practice is to make use of those designations



(270)

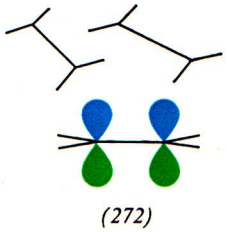


(271)

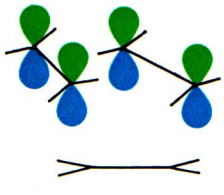
which most explicitly reveal the largest extent of delocalization in the generalized molecular orbitals – in this case *(265)* and *(267)*, rather than *(270)* and *(271)*. In any event, no other acceptable orbitals are available for the case at hand, and it is important to realize that in consequence there is no element either of arbitrariness or of ambiguity in the conclusions we shall reach.

We next note that the six electrons in the π orbitals of the product ethylene molecules must be assigned to the generalized molecular orbitals *(272)*–*(274)*.

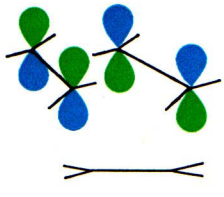
One further, and very important, factor must now be recognized. The geometrical relationships among starting material and products, as revealed by inspection of *(275)*, require that in the course of reaction, rotations about the axes 1,2 and 3,4 must take place, in such wise as to bring the substituent groups at C-1 and C-2 on the one hand, and those at C-3 and C-4 on the other, into the common planes in which they lie in the respective product ethylene molecules. *A priori*, on purely geometrical grounds, these displacements might be *conrotatory (276)* or *disrotatory (277)*, and there are, of



(272)

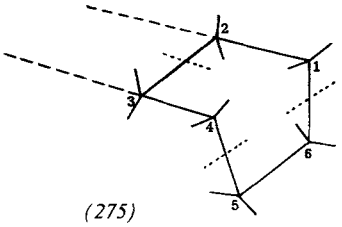


(273)



(274)

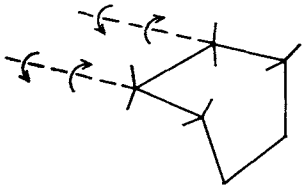
[128] *H. E. Zimmerman, R. W. Binkley, R. S. Givens*, and *M. A. Sherwin*, J. Amer. chem. Soc. *89*, 3932 (1967).



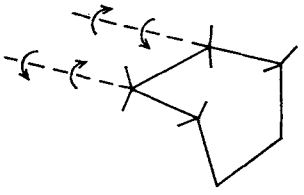
(275)

course, in each case two possibilities [arrows in *(276)* and *(277)*].

Now we are properly prepared to annihilate our cyclohexane molecule. We shall see that there are *two*,



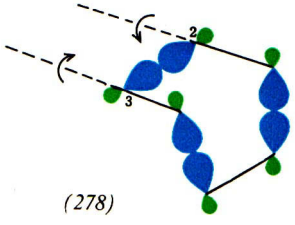
(276)



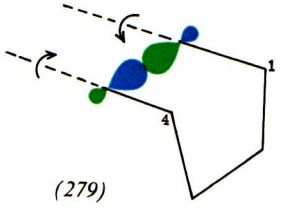
(277)

and only two, symmetry-allowed ways in which this decomposition may occur – given the transition state geometry we have chosen.

1. Let us first permit the two electrons in orbital *(265)* to enter orbital *(272)*, as of course they may do with conservation of orbital symmetry. It is then at once clear that the two electrons in orbital *(267)* must occupy orbital *(278)* of the product array – *and that of the rotational displacements adumbrated above, the inward disrotatory one (278)* must obtain. It remains only to place the remaining σ pair – those in the orbital *(266)*



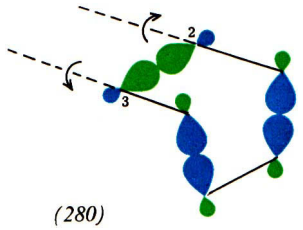
(278)



(279)

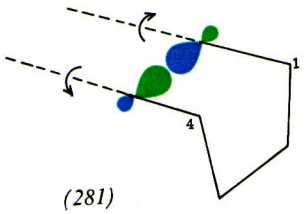
at the outset of reaction – into orbital *(274)* of the product assemblage; a special point here is that mixing of the occupied orbital *(266)* with the unoccupied antibonding backbone σ* orbital *(279)* is consistent with the same inward disrotatory motion about axes 1,2 and 3,4. The symmetry-allowed process which we have now depicted in full detail may be designated a $-[\pi 2_s+\pi 2_s+\pi 2_s]$ cycloreversion reaction. Naturally, a precisely analogous analysis applies to the reverse process – the symmetry-allowed $[\pi 2_s+\pi 2_s+\pi 2_s]$ cycloaddition reaction.

2. Alternatively, let us first permit the two electrons in orbital *(267)* to take up new positions in orbital *(272)* as cycloreversion proceeds Now those in orbital *(265)* have no choice but to enter orbital *(273)* of the product array. And, in sharp contrast to the case discussed above, the cleavage of the backbone bond (2,3) must be accompanied by *outward* disrotatory displacements *(280)*. As before, the remaining pair, occupying orbital



(280)

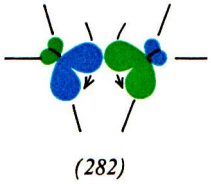
(266), takes up new positions in orbital *(274)*, and, as before, mixing of *(266)* with the unoccupied antibonding backbone σ* orbital *(281)* is consistent with the outward disrotatory motion required by the symmetry relationships between orbitals *(280)* and *(274)*. The process here delineated may be designated a symme-



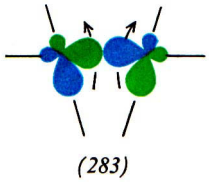
(281)

try-allowed $-[\pi 2_s+\pi 2_a+\pi 2_a]$ cycloreversion reaction; it is the reverse of the allowed $[\pi 2_s+\pi 2_a+\pi 2_a]$ cycloaddition reaction.

Thus, we have found that there are two possible symmetry-allowed [2+2+2] cyclic processes which proceed through a transition state possessing a single plane of symmetry. Structural, steric, and entropy factors may favor one or the other of these paths in various special circumstances. Is one or the other favored by inherent stereoelectronic factors not so far delineated? Indeed, when one considers in greater detail the mixing of the antisymmetric bonding orbital *(266)* with the antisymmetric antibonding orbital *(279)* [or *(281)*], it is found that the *s*, *s*, *s* process is favored over the alternative *s*, *a*, *a* path. Thus, the dihedral angle between the relevant orbitals at the outset of reaction is represented in plan in *(282)* and *(283)*. The geometry of the alternatives indicates clearly that favorable, energy-lowering overlap will develop more readily from the motions depicted in *(282)*, and that the ascent to the transition state



(282)



(283)

will be considerably steeper for the *s*, *a*, *a* process of *(283)* [128a].

Several facets of the [2+2+2] reactions deserve further, if now briefer, consideration. The reader may wish to sharpen his apprehension of symmetry considerations through verifying for himself the propositions which follow:

a) There is a continuum of topologically equivalent symmetry-allowed thermal $[\pi 2_s+\pi 2_s+\pi 2_s]$ processes, whose transition states vary from that depicted above to one whose geometry resembles that of a chair cyclohexane ring.

b) There are two further symmetry-allowed thermal $[\pi 2_s+\pi 2_a+\pi 2_a]$ processes, topologically different from the one described above, which proceed through enantiomeric transition states possessing a two-fold axis of symmetry.

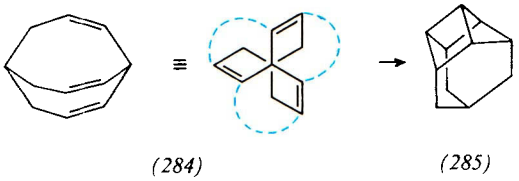
c) There are *no* symmetry-allowed thermal $[\pi 2_s+\pi 2_s+\pi 2_a]$ processes.

d) There are *no* symmetry-allowed thermal $[\pi 2_a+\pi 2_a+\pi 2_a]$ processes.

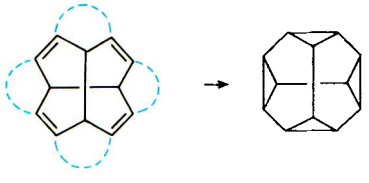
e) For reactions involving occupied antibonding levels – for example, reactions of molecules in photochemically excited states – there are no *s*, *s*, *s* or *s*, *a*, *a* symmetry-allowed [2+2+2] processes, but there are two allowed enantiomeric *s*, *s*, *a*, as well as two permitted, and also enantiomeric, *a*, *a*, *a* paths.

f) Every all-*antara* [2+2+2+. . .] combination is symmetry-forbidden in ground states, and symmetry-allowed for excited states in which the antibonding orbital of one participating ethylene unit is occupied.

Lest any might cavil at the discussion of processes which on casual consideration could appear to be so improbable of realization as only to merit summary dismissal, we may allude to the essentially strain-free, as yet unknown, molecules *(284)* and *(286)*, whose double bonds are so constrained by the frameworks in which they are embedded as to favor photochemical conversion to *(285)* and *(287)*, by the all-*antara* paths mentioned above.



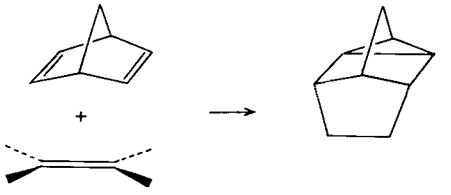
(284) *(285)*



(286) *(287)*

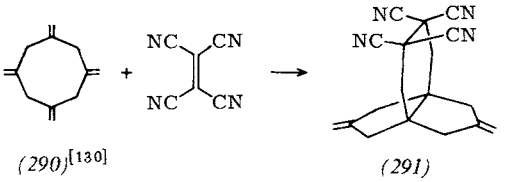
[128a] Since the above was written, this prediction has received elegant experimental confirmation: *J. A. Berson* and *S. S. Olin*, J. Amer. chem. Soc. *91*, 777 (1969).

It remains to exemplify some of the above processes through presentation of selected known cases. Most of those so far discovered fall in the symmetry-allowed thermal *s*, *s*, *s* class. Perhaps best known is the addition of olefins to bicycloheptadiene [129] [*(288)*→*(289)*].

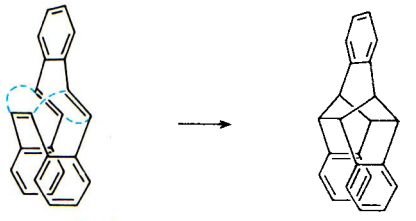


(288) *(289)*

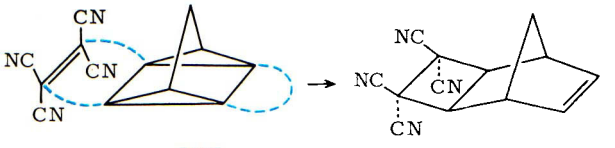
Further examples in this group are the reactions *(290)*→*(291)*, *(292)*→*(293)*, and *(294)*→*(295)*.



(290) [130] *(291)*



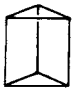
(292) [131] *(293)*



(294) [132] *(295)*

6.4. Prismane

To what does this fantastic molecule *(296)* owe its capacity to survive? In it there is stored at least ninety kilocalories of energy more than is contained in its iso-



(296)

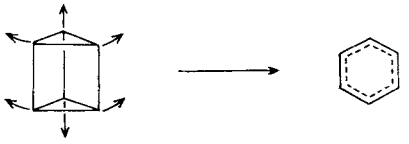
[129] *Inter alia: A. T. Blomquist* and *Y. C. Meinwald*, J. Amer. chem. Soc. *81*, 667 (1959); *R. C. Cookson*, *S. S. H. Gilani*, and *I. D. R. Stevens*, Tetrahedron Letters *1962*, 615; *H. K. Hall*, J. org. Chem. *25*, 42 (1960).

[130] *J. K. Williams* and *R. E. Benson*, J. Amer. chem. Soc. *84*, 1257 (1962).

[131] *H. A. Staab*, *F. Graf*, and *B. Junge*, Tetrahedron Letters, *1966*, 743.

[132] *C. D. Smith*, J. Amer. chem. Soc. *88*, 4273 (1966). *Cf.* also *H. Prinzbach*, Pure appl. Chem. *16*, 24 (1968); *H. Prinzbach* and *J. Rivier*, Angew. Chem. *79*, 1102, (1967); Angew. Chem. internat. Edit. *6*, 1069 (1967).

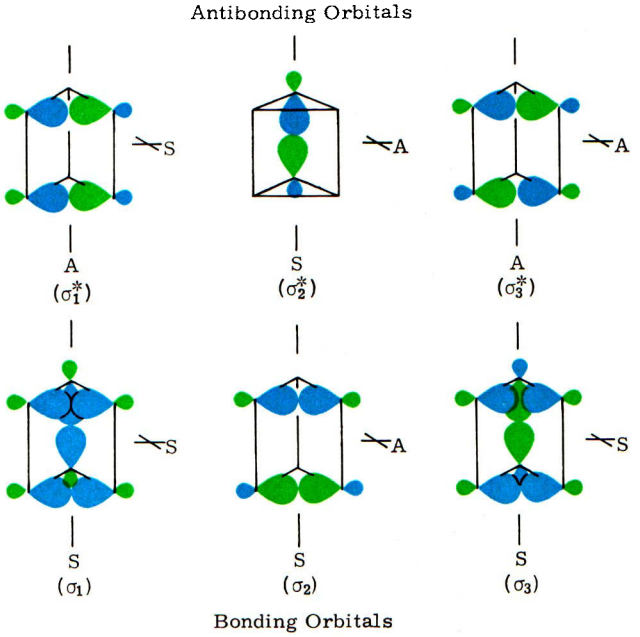
mer benzene[133]; a graceful process of atomic displacements may readily be envisaged for the conversion of the one molecule into the other [*cf.* *(297)→(298)*]. Yet, no less than a further thirty-three



(297) *(298)*

kilocalories must be added to the already exorbitantly strained hexamethylprismane molecule in order to bring about its conversion to hexamethylbenzene[133]. To the mind uninformed by an appreciation of the limitations placed upon bond-breaking and bond-making processes by orbital symmetry relationships, the excess energy of the prismane molecule must have the aspect of an angry tiger unable to break out of a paper cage.

When we examine this situation in detail from the vantage point of the principle of orbital symmetry conservation, we shall see that there is no paper cage, but rather one quite properly barred to contain its tiger. First, we must construct the generalized molecular orbitals *(299)* into which must be placed the six electrons



(299)

of the three σ bonds which must be broken if prismane is to be converted to benzene.

Now, let us break the three σ bonds, *while conserving the symmetry imposed upon the orbitals of the prismane molecule by its geometry*; note that σ_2 and σ_2^*, of like symmetry, interact to produce a new pair, represented by the sum and the difference of the originals. The specified changes are shown in Figure 27.

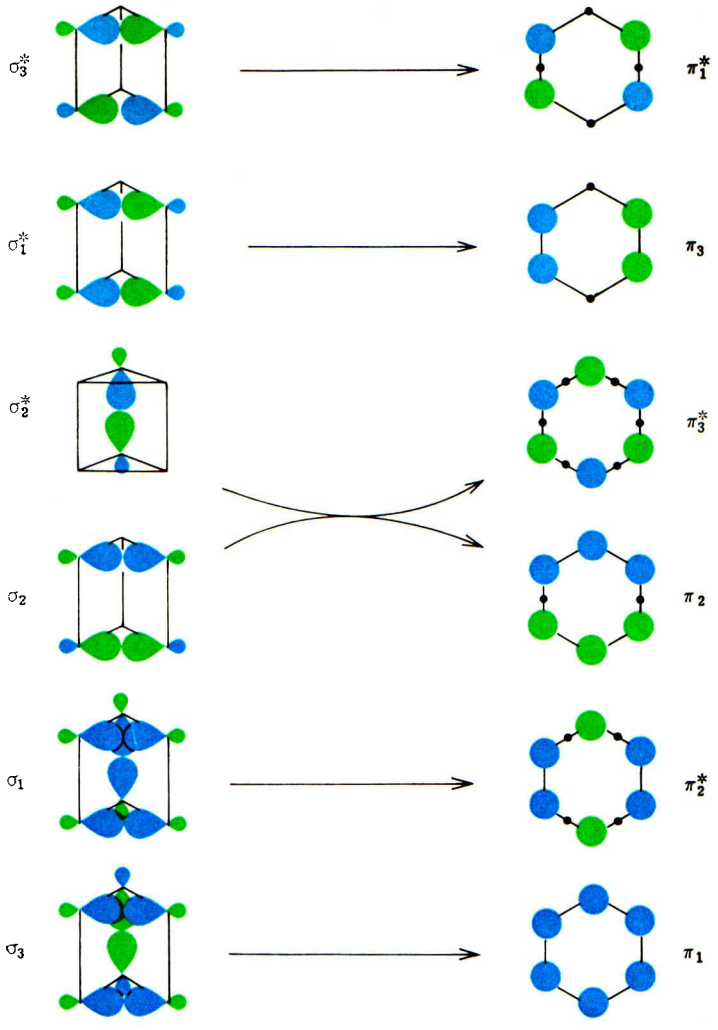


Figure 27. Formation of the π orbitals of benzene from σ orbitals of prismane.

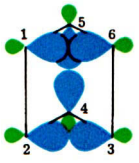
What are the new orbitals thus generated? They are precisely the molecular orbitals of the benzene molecule. But while two of the bonding σ orbitals of prismane (σ_2 and σ_3) have transformed into two bonding orbitals of benzene (π_2 and π_1), *the third becomes an antibonding orbital of the product* ($\sigma_1 \rightarrow \pi_2^*$). Physically, this correlation introduces an antibonding, energy-raising component into the transition state for the transformation. It is that component which makes the transformation of prismane into benzene symmetry-forbidden, and permits the former to exist.

Further insight into the basic nature of symmetry-determined bonding relationships can be gained by amplifying our discussion of prismane in a number of ways. First, let us note that, in a formal sense, the transformation of prismane into benzene might be regarded as a $-[\pi 2_s + \pi 2_a + \pi 2_a]$ cycloreversion reaction [*(300)→(301)*]. We have seen in the preceding section that thermal reactions of that class are symmetry-allowed. What then excludes the prismane→benzene

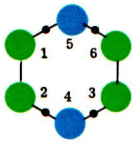
(300) *(301)*

[133] *J. F. M. Oth*, Angew. Chem. *80*, 633 (1968); Angew. Chem. internat. Edit. *7*, 646 (1968); Rec. Trav. chim. Pays-Bas *87*, 1185 (1968).

transformation from the symmetry-allowed class to which it might formally be assigned on casual inspection? When we scrutinize the offending bonding-antibonding correlation of the orbitals σ_1 *(302)* and π_2^* *(303)*, we see at once that it is the development of nodal, antibonding, energy-raising relationships at the 1,5, 5,6 , 2,4 , and 3,4 bonds, necessitated by the presence of the invariant framework σ bonds in the prismane molecule, which differentiates the prismane→benzene



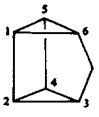
(302)



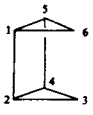
(303)

transformation from the general [2+2+2] cycloreversion reaction. When, as in the latter, those σ bonds are absent, these antibonding, energy-raising components are also absent.

The point may be illustrated further by considering certain molecules closely related to prismane. Consider first quadricyclene *(304)* and the tricyclohexane *(305)*.

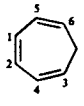


(304)

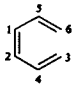


(305)

These molecules might at first sight be expected to be susceptible of symmetry-allowed transformation to cycloheptatriene *(306)* and hexatriene *(307)*, but analysis along the lines set down above shows that, as in the case of prismane, the presence of the framework σ bonds places the changes in the symmetry-forbidden category. It is worthy of note that, in fact, quadricyclene is not converted to cycloheptatriene, even at very high

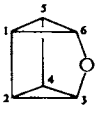


(306)

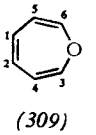


(307)

temperatures [134]. In that light, the oxygen analogue *(308)* is of special interest. In this case, the product of a $-[\pi 2_s+\pi 2_a+\pi 2_a]$ cycloreversion is oxepine *(309)*, and the orbital correlation analogous to that which leads in the other cases to an antibonding level, gives now the highest occupied ground-state level, which is probably weakly bonding. It is gratifying to note that deri-



(308)

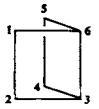


(309)

[134] *H. Prinzbach* and *J. Rivier*, Tetrahedron Letters *1967*, 3713.

vatives of the oxa analogue are smoothly transformed to oxepines when heated [135,136].

Another relative of the prismane molecule is the bicyclo[2.2.0]hexane *(310)*. In this case, lacking as it does σ



(310)

(311)

bonds joining C-1 to C-5, and C-2 to C-4, no offensive nodes develop as the transition state for $-[\pi 2_s+\pi 2_a+\pi 2_a]$ cycloreversion is approached; consequently, the thermal transformation of *(310)* to ethylene and butadiene *(311)* is symmetry-allowed. In fact, it has not as yet been observed. When the unsubstituted bicyclohexane

(312)

(313)

itself is heated, it is converted to 1,5-hexadiene *(312)* [137] – either by a two-step mechanism involving an intermediate *(313)*, or by a symmetry-allowed $[\sigma 2_s+\sigma 2_a]$ path.

6.5. [2+2+2+2] Cycloadditions

The $[\pi 2+\pi 2+\pi 2+\pi 2]$ cycloaddition reaction is symmetry-allowed:

a) For ground state reactants, when an *odd* number of components is involved in a suprafacial manner.

b) For reactions in which one component is in an excited state, when an *even* number of components is involved in a suprafacial manner.

Obviously, entropy factors render polymolecular reactions of this type very highly improbable. Just as obviously, this difficulty can be surmounted by the manoeuvre of building all the components into a single molecule, geometrically prepared for their eventual dispersal. Such examples have already been mentioned above [*(284)* and *(286)*].

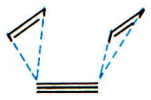
Symmetry-allowed many-component fragmentations are also opposed by a special factor; for each σ bond which is transformed into a π bond an endothermicity of some twenty kilocalories must be expected.

There are instances of $[\pi 2+\pi 2+\pi 2+\pi 2]$ cycloadditions masquerading as other processes. Consider for exam-

[135] *H. Prinzbach, M. Argüelles*, and *E. Druckrey*, Angew. Chem. *78*, 1057 (1966); Angew. Chem. internat. Edit. *5*, 1039 (1966).

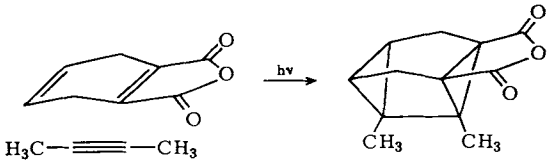
[136] *H. Prinzbach, P. Vogel*, and *W. Auge*, Chimia *21*, 469 (1967).

[137] *C. Steel, R. Zand, P. Hurwitz*, and *S. G. Cohen*, J. Amer. chem. Soc. *86*, 679 (1964).

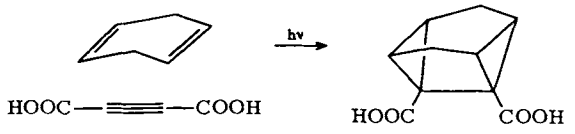


(314)

ple the double cycloaddition of an acetylene to two ethylenes *(314)*. Examination of the orbitals reveals that the two acetylene π bonds are acting independently. At least two such reactions [*(315)*→*(316)* and *(317)*→*(318)*] have been observed [138,139].

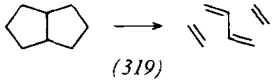


(315) (316)



(317) (318)

An amusing fragmentation would be the reaction *(319)*; the analogous decomposition of pentalene to di-



(319)

acetylene and two acetylenes has been suggested in the literature as a theoretical possibility [140]; we now recognize this to be a symmetry-forbidden thermal process.

We defined as a sigmatropic change of order [i,j] the migration of a σ bond, flanked by one or more π electron systems, to a new position whose termini are $i-1$ and $j-1$ atoms removed from the original bonded loci, in an uncatalyzed intramolecular process. Thus, the well-known Claisen and Cope rearrangements are sigmatropic changes of order [3,3].

A priori, there are two topologically distinct ways of effecting a sigmatropic migration. These are illustrated in Figure 28 for the [1,5] shifts of a hydrogen atom. In the first, *suprafacial* process, the transferred hydrogen atom is associated at all times with the same face of the π system. In the second, *antarafacial* process, the migrating atom is passed from the top face of one carbon terminus to the bottom face of the other.

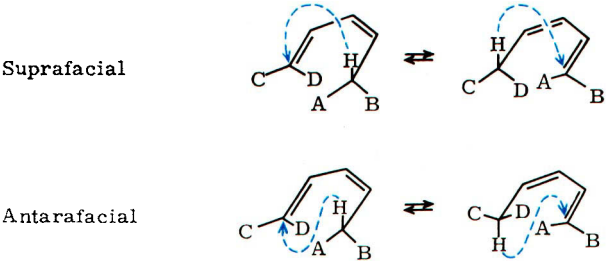


Figure 28. Suprafacial and antarafacial [1,5] shifts of a hydrogen atom.

For the analysis of these reactions correlation diagrams are not relevant since it is only the transition state and not the reactants or products which may possess molecular symmetry elements. We shall present

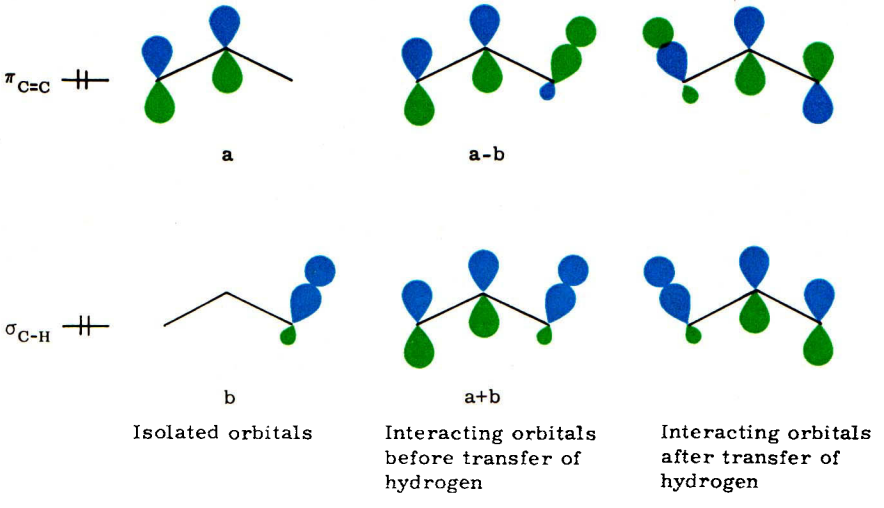


Figure 29. Conservation of orbital symmetry in a suprafacial [1,3] hydrogen shift.

several equivalent methods for analyzing these reactions.

1. The use of the principle of *conservation of orbital symmetry* is here illustrated for the case of a supra-

[138] *R. Askani*, Chem. Ber. *98*, 3618 (1965).

[139] *M. Takahashi, Y. Kitahara, I. Murata, T. Nitta*, and *M. C. Woods*, Tetrahedron Letters *1968*, 3387.

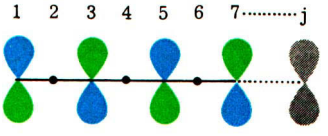
[140] *H. C. Longuet-Higgins* in: Theoretical Organic Chemistry. The Kekulé Symposium. Butterworths, London 1959, p. 17.

facial [1,3] hydrogen shift. The relevant correlations are shown in Figure 29. Clearly, two electrons can enter a bonding orbital, either σ or π, of the product, but the other two must be placed either in a σ^* or a π^* orbital, if orbital symmetry is to be conserved. *The reaction is symmetry-forbidden.*

2. In the [1,j] sigmatropic migration of hydrogen within an all-*cis*-polyene framework [*(320)*→*(321)*], one may envisage the transition state as made up by the combination of the orbital of a hydrogen atom with those of a radical containing $2k+3$ π electrons. The highest oc-

$$\underset{(320)}{R_2\overset{1}{C}=\overset{2}{C}H\text{-}(CH=CH)_k\text{-}\overset{j}{C}HR_2} \longrightarrow \underset{(321)}{R_2\overset{1}{C}H\text{-}(CH=CH)_k\text{-}CH=CR_2}$$

cupied orbital of the framework system is the nonbonding allylic orbital which possesses the symmetry shown in *(322)*. Consider a hydrogen atom bonding to



(322)

the termini of such systems. In order to avoid a high energy orbital in the transition state, it is required that positive overlap between the framework orbital and the migrating hydrogen orbital be maintained. The result is symmetry-allowed suprafacial migration for odd k, while the antarafacial path must be followed for even k.

3. Let us now examine the transition state from a different, but equivalent, viewpoint. First, we write down an explicit three-center bond involving the termini of the carbon chain and the migrating hydrogen atom. The three-center bond has the typical level pattern indicated in Figure 30. There remains a $2k+1$ π orbital system in the carbon chain. The molecular orbitals of

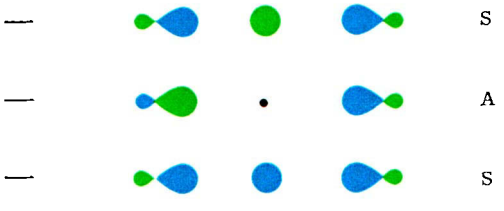


Figure 30. Orbital relationship in a three-center bond. Note that the symmetry labels are invariant whether a mirror plane or a two-fold axis of rotation is used as the basis for classification.

this remnant are next classified with respect to the symmetry element (two-fold axis or mirror plane) present in the transition state. There now arise two cases, differing in the symmetry of the nonbonding orbital of the remnant. In the first case (Figure 31) this orbital is antisymmetric and interacts strongly with the central orbital of the three-center bond. In the second case (Figure 32) the remnant orbital is symmetric and cannot interact in a similar way. The presence of the interaction

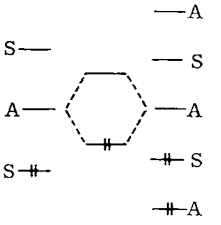


Figure 31. Interaction of nonbonding antisymmetric levels of three-center bond and remnant, for the antarafacial [1,7] shift of a hydrogen atom ($k = 2$).

typically stabilizes one level, and destabilizes the other. Now, since there are in all $2k+4$ electrons to be accommodated $-$ $2k$ electrons in bonding polyenyl levels, and

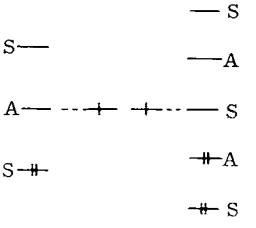


Figure 32. Noninteraction of nonbonding levels of three-center bond and remnant, for the suprafacial [1,7] shift of a hydrogen atom ($k = 2$).

2 in the lowest orbital of the three-center bond $-$ there remain 2 electrons to be placed in the lower component of this interacting pair. It follows that for the ground-state reaction, the first case is symmetry-allowed. Thus, in general, in order that the nonbonding orbital of the $(2k+1)$-orbital remnant π system shall be antisymmetric under the appropriate symmetry operation, these reactions must proceed through a transition state having a mirror plane when k is odd, or one having a two-fold axis when k is even.

For excited-state reactions, as in the cases of electrocyclic reactions and cycloadditions, the selection rules are precisely reversed, as compared with those for ground states.

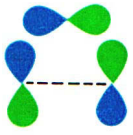
For sigmatropic changes of order [i,j] in which both i and j are greater than 1, the migrating group of the above analyses consists of more than one atom, and appropriate topological distinctions must be made in

$i+j$	Ground State	Excited State
$4q$	antara-supra supra-antara	supra-supra antara-antara
$4q+2$	supra-supra antara-antara	antara-supra supra-antara

Figure 33. Selection rules for sigmatropic reactions of order [i,j] with i and $j > 1$.

relation to *both* π systems through which the σ bond is moving. The selection rules are summarized in Figure 33.

In the above treatment of [1,j] sigmatropic changes, we have considered only those cases in which a σ orbital of the migrating group interacts with a π system in the transition state, and migration occurs *with retention of configuration at the shifting site*. When the migrating group possesses an accessible π orbital and is not so substituted as to create an impossible steric situation in the transition state, alternative processes using that π orbital must be considered. Clearly, such changes *must proceed with inversion at the migrating center* [*cf. (323)*], and the selection rules are precisely reversed from those given in Figure 33.



(323)

A number of special points pertinent to sigmatropic changes should be noted.

a) Antarafacial processes are obviously impossible for transformations which occur within small or medium-sized rings.

b) Distortion of the carbon framework, with concomitant impairment of coupling within the π system, may render a symmetry-allowed process difficult or impossible of realization; for example, this factor makes the antarafacial process difficult or perhaps impossible in the [1,3] case, but is not an impediment for the [1,7] reaction.

c) A cyclopropane ring may replace a π bond in the framework system for a sigmatropic change.

d) Orbital symmetry arguments are applicable to sigmatropic changes within ionic species. Thus, the suprafacial [1,2] shift within a carbonium ion is symmetry-allowed and is very well known. The predicted [1,4] shift with inversion of the migrating group, within a but-2-en-1-yl cation has recently been observed. We may expect that the [1,6] shift within a hexa-2,4-dien-1-yl cation will take place through a readily accessible suprafacial transition state.

It remains to point out that the insights afforded by the discussions presented in the preceding sections allow us to view sigmatropic changes as cycloaddition reactions. Thus, the [1,3] sigmatropic process *(324)*→*(325)*

(324) *(325)*

is a $[\sigma 2+\pi 2]$ reaction, and the [3,3] sigmatropic rearrangement *(326)*→*(327)* is a $[\pi 2+\sigma 2+\pi 2]$ concerted cycloaddition.

(326) *(327)*

From this standpoint, let us now examine in detail the stereochemical aspects of the [1,3] sigmatropic change. We know that the symmetry-allowed processes must fall in either the $[\sigma 2_s+\pi 2_a]$ or the $[\sigma 2_a+\pi 2_s]$ class. All of the possibilities are shown in Figure 34. It is at once apparent that the first two alternatives depicted in Figure 34 are simply different ways of regarding one and the same physical process. Consequently, the analysis yields, as it must, precisely the conclusions reached in our prior discussions of sigmatropic reactions.

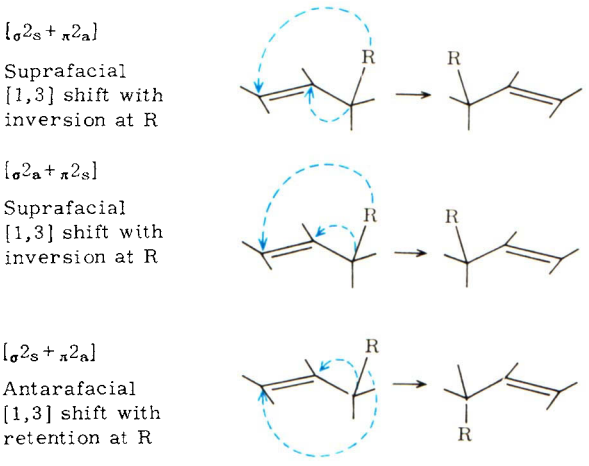


Figure 34. Stereochemical possibilities in sigmatropic [1,3] shifts.

7.1. Sigmatropic Reactions Exemplified

Few thermal uncatalyzed [1,3] shifts are known [141]. Those which formally might be considered in this category, such as the vinylcyclopropane→cyclopentene rearrangement, proceed with such high activation energies (*ca.* 50 kcal/mole) that the energy surface for concerted reaction cannot be far removed from that for alternative stepwise processes. None the less, *Berson* and *Nelson* [142] recently made the dramatic observation that *(328)* undergoes a concerted symmetry-allowed suprafacial [1,3] shift, *with inversion at the migrating center* [starred in *(328)*], to give *(329)*, at 307 °C.

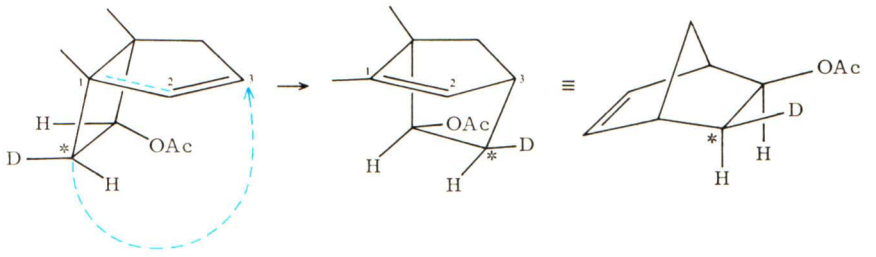
The triene *(330)* owes its relative stability [143] to the requirement of a symmetry-forbidden [1,3] shift for an uncatalyzed rearrangement to toluene.

---

[141] For example, [1-^{14}C]-propylene does not rearrange to [3-^{14}C]-propylene: *B. Sublett* and *N. S. Bowman*, J. org. Chem. *26*, 2594 (1961).

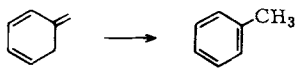
[142] *J. A. Berson* and *G. L. Nelson*, J. Amer. chem. Soc. *89*, 5303 (1967); *J. A. Berson*, Accounts Chem. Res. *1*, 152 (1968).

[143] *W. J. Bailey* and *R. A. Baylouny*, J. org. Chem. *27*, 3476 (1962).



(328) (329)

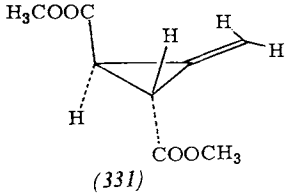
The rearrangement of the ester *(331)* of Feist's acid is an especially interesting [1,3] sigmatropic transformation. Studies on the optically active substance have dem-



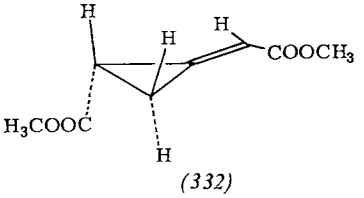
(330)

onstrated that the reaction occurs with high stereospecificity [144]. Of the two *a priori* possible symmetry-allowed skeletal processes – [1,3] suprafacial migration with inversion at the migrating atom, and [1,3] antarafacial shift with retention – the latter is rendered inaccessible by the constraints imposed by the σ skeleton.

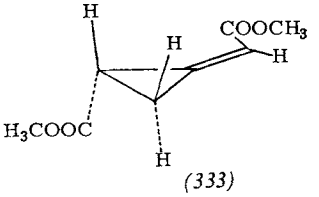
Since substituents are present, the allowed and accessible process may be realized in two electronically identical, but sterically different, ways. Consequently, we may predict that *(331)* must be transformed into *(332)* and/or *(333)*; the evidence is now conclusive [144] that the two isomers actually produced are the predicted ones.



(331)

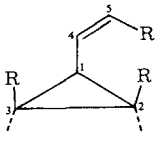


(332)

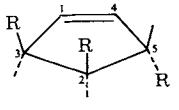


(333)

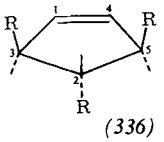
We have mentioned above that the activation energy for the vinylcyclopropane→cyclopentene conversion [145,146] is *ca.* 50 kcal/mole [146]. The bond-breaking process in cyclopropane itself requires an activation energy of 63 kcal/mole [147]; allylic stabilization has been estimated at *ca.* 13 kcal/mole [148]. Consequently, if full use be made of the available allylic stabilization energy in a diradical intermediate, a two step, non-concerted path for the conversion of vinylcyclopropane to cyclopentene is not thermodynamically unreasonable. Some preliminary studies have yielded results consistent with such a mechanism [149]. Nevertheless, in view of the recently established occurrence of symmetry-allowed concerted processes, despite extraordinarily unfavorable geometric constraints, it is worth while to consider the stereochemical consequences of the possible concerted processes for the vinylcyclopropane→cyclopentene change. Consider the maximally labeled derivative *(334)*; the symmetry-allowed reactions are:



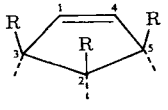
(334)



(335)



(336)



(337)

a) an antarafacial [1,3] shift of bond 1,2 to C-5, with retention at C-2, leading to *(335)*;

b) a suprafacial [1,3] shift of bond 1,2 to C-5, with inversion at C-2, leading to *(336)*.

The isomer *(337)* cannot be produced in a symmetry-allowed process.

Photochemical [1,3] rearrangements, symmetry-allowed as suprafacial shifts, have been observed in a large number of cases [150].

[144] *W. von E. Doering*, personal communication; *cf. E. F. Ullman*, J. Amer. chem. Soc. *82*, 505 (1960).

[145] *C. G. Overberger* and *A. E. Borchert*, J. Amer. chem. Soc. *82*, 1007 (1960).

[146] *M. C. Flowers* and *H. M. Frey*, J. chem. Soc. *1961*, 3547, *R. J. Ellis* and *H. M. Frey*, *ibid. 1964*, 959, 4188; *C. J. Elliot* and *H. M. Frey*, *ibid. 1965*, 345; *A*, *1966*, 553; *C. A. Wellington*, J. physic. Chem. *66*, 1671 (1962); *H. M. Frey* and *D. C. Marshall*, J. chem. Soc. *1962*, 3981; *G. R. Branton* and *H. M. Frey*, *ibid. 1966*, 1342.

[147] *B. S. Rabinowitch*, *E. W. Schlag*, and *K. B. Wiberg*, J. chem. Physics *28*, 504 (1958); *B. S. Rabinowitch* and *E. W. Schlag*, J. Amer. chem. Soc. *86*, 5996 (1960).

[148] *K. W. Egger*, *D. M. Golden*, and *S. W. Benson*, J. Amer. chem. Soc. *86*, 5420 (1964).

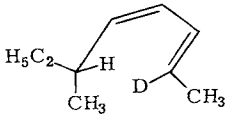
[149] *M. R. Willcott* and *V. M. Cargle*, J. Amer. chem. Soc. *89*, 723 (1967); *W. R. Roth*, personal communication.

[150] *W. G. Dauben* and *W. T. Wipke*, Pure appl. Chem. *9*, 539 (1964). *J. J. Hurst* and *G. M. Whitham*, J. chem. Soc. *1960*, 2864; *R. C. Cookson*, *V. N. Gogte*, *J. Hudec*, and *N. A. Mirza*, Tetrahedron Letters *1965*, 3955; *W. F. Erman* and *H.C. Kretschmar*, J. Amer. chem. Soc. *89*, 3842 (1967); *R. F. C. Brown*, *R. C. Cookson*, and *J. Hudec*, Tetrahedron *24*, 3955 (1968); *R. C. Cookson*, Chemistry in Britain *5*, 6 (1969); *E. Baggiolini*, *H. P. Hamlow*, *K. Schaffner*, and *O. Jeger*, Chimia *23*, 181 (1969).

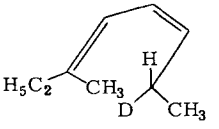
Specific thermal [1,5] shifts have been observed in a great number of cases [151]. The simplest case of a [1,5] shift in a 1,3-pentadiene was studied by *Roth* and *König* [152]. They compared the rearrangements of *(338)* and *(339)*, and observed a large kinetic isotope

(338) *(339)*

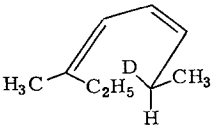
effect of 12.2 at 25 °C, consistent with a highly symmetrical transition state in a concerted process. The activation energy for the rearrangement is in the neighborhood of 35 kcal/mole. Direct confirmation of the concerted, suprafacial character of the [1,5] sigmatropic shift of a hydrogen atom has been most elegantly provided by the same investigators [153], who demonstrated the completely stereospecific conversion of *(340)* into *(341)* and *(342)*.



(340)



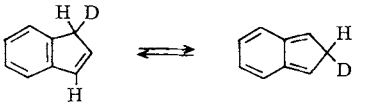
(341)



(342)

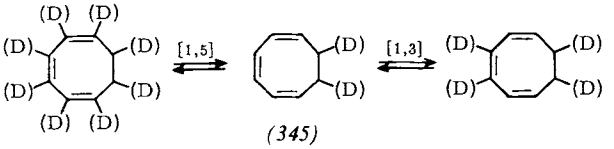
Numerous sequential stereospecific [1,5] shifts have been observed in cyclopentadienes and cycloheptatrienes [154–156].

Roth has beautifully shown the absolute preference for [1,5] over [1,3] shifts in cyclic systems. Thus, a [1,5] shift scrambles the deuterium label in *(343)* over all nonaromatic positions at elevated temperatures [155], despite the necessity of proceeding through the unstable isoindene *(344)*. In sharp contrast, the base-catalyzed reaction proceeds with a stereospecific [1,3] shift [157].



(343) *(344)*

Still another test for the possible occurrence of a thermal [1,3] shift proved negative [158]. The 7,8 dideuterium labeled cycloocta-1,3,5-triene *(345)*, through a series of reversible [1,3] sigmatropic shifts, involving the isomeric cycloocta-1,3,6-triene, would distribute the label statistically over all ring positions. On the other hand, a sequence of [1,5] shifts would place the label in positions 3, 4, 7, and 8 only; the latter result is experimentally observed.



(345)

Photochemical [1,5] shifts of as yet undetermined stereochemistry are known in open, but *not* in cyclic hydrocarbons [159] and in heterocycles [160].

Berson and *Willcott* [161] have observed a remarkable series of isomerizations of methyl-substituted cycloheptatrienes. Their results, summarized in Figure 35, are consistent with a sequence of [1,5] sigmatropic rearrangements and electrocyclic reactions. Our prediction is that the suprafacial [1,5] shifts must proceed

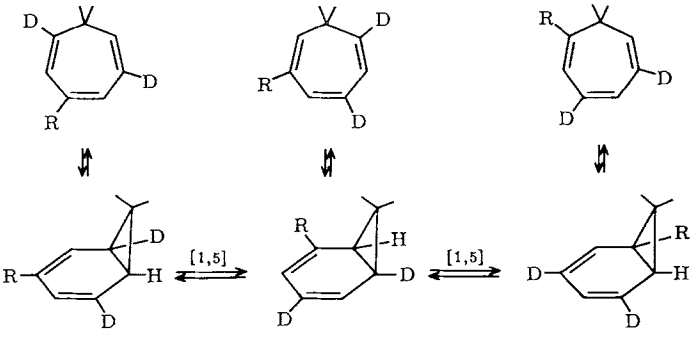


Figure 35. Isomerizations of methyl-substituted cycloheptatrienes through sequences of [1,5] sigmatropic rearrangements and electrocyclic reactions.

with retention at the shifting center. This condition implies that in each shift substituents on the cyclopropane ring pivot 180 °. The beautiful experimental test proposed but as yet not completed by *Berson* and *Willcott* [161] necessitates the pyrolysis of an optically active compound *(346)*. Symmetry-forbidden [1,5]

[151] References to the literature may be found in *D. S. Glass, R. S. Boikess*, and *S. Winstein*, Tetrahedron Letters *1966*, 999. An interesting recently discovered [1,5] shift of a methyl group is described by *R. Grigg, A. W. Johnson, K. Richardson*, and *K. W. Shelton*, Chem. Commun. *1967*, 1192; *cf.* also *V. Boekelheide* and *E. Sturm*, J. Amer. chem. Soc. *91*, 902 (1969).

[152] *W. R. Roth* and *J. König*, Liebigs Ann. Chem. *699*, 24 (1966). See also *H. Kloosterziel* and *A. P. ter Borg*, Rec. Trav. Chim. Pays-Bas *84*, 1305 (1965).

[153] *W. R. Roth* and *J. König*, personal communication.

[154] *V. A. Mironov, E. V. Sobolev*, and *A. N. Elizarova*, Tetrahedron *19*, 1939 (1963); *S. McLean* and *R. Haynes*, Tetrahedron Letters *1964*, 2385.

[155] *W. R. Roth*, Tetrahedron Letters *1964*, 1009.

[156] *A. P. ter Borg, H. Kloosterziel*, and *N. van Meurs*, Rec. Trav. Chim. Pays-Bas *82*, 717, 741, 1189 (1963); *E. Weth* and *A. S. Dreiding*, Proc. chem. Soc. *1964*, 59; *K. W. Egger*, J. Amer. chem. Soc. *89*, 3688 (1967).

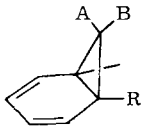
[157] *G. Bergsson* and *A. Weidler*, Acta chem. scand. *17*, 1798 (1963); *A. Weidler, ibid. 17*, 2724 (1963); *A. Weidler* and *G. Bergsson, ibid. 18*, 1484, 1487 (1964); *J. Almy, R. T. Uyeda*, and *D. J. Cram*, J. Amer. chem. Soc. *89*, 6768 (1967), and references therein.

[158] *W. R. Roth*, Liebigs Ann. Chem. *671*, 25 (1964).

[159] For example: *R. Srinivasan*, J. Amer. chem. Soc. *84*, 3982 (1962); *K. J. Crowley*, Proc. chem. Soc. *1964*, 17; *H. Prinzbach* and *E. Druckrey*, Tetrahedron Letters *1964*, 2959.

[160] *E. F. Zwicker, L. I. Grossweiner*, and *N. C. Yang*, J. Amer. chem. Soc. *85*, 2671 (1963); *G. Wettermark*, Photochem. Photobiol. *4*, 621 (1965); *K. R. Huffman, M. Loy*, and *E. F. Ullman*, J. Amer. chem. Soc. *87*, 5417 (1965); *G. Büchi* and *N. C. Yang, ibid. 79*, 2318 (1957).

[161] *J. A. Berson* and *M. R. Willcott, III*, J. Amer. chem. Soc. *87*, 2751, 2752 (1965); *88*, 2494 (1966).

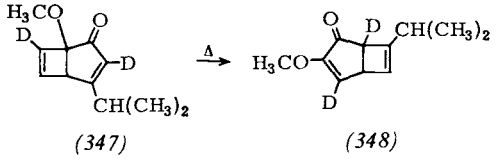


(346)

shifts with inversion – the course which would be followed were the principle of least motion determinative – would result in racemization, while the predicted shifts with retention would lead to no loss of optical activity (Figure 36).

Figure 36. Schematic top view of the possible placements of substituents on a cyclopropane ring migrating around a cyclohexadiene ring by a series of [1,5] sigmatropic shifts, with retention (left) or inversion (right). Note that for clarity the cyclopropane rings are assumed to be perpendicular to the plane of the page, and are not seen.

The Cope and Claisen rearrangements, both [3,3] sigmatropic shifts, are such common reactions that we could not possibly do justice to the many examples studied [162]. These rearrangements are allowed both in a *supra-supra* and an *antara-antara* manner. At first sight it would seem obvious that the transition state for the latter is sterically unattainable. And yet an *antara-antara* Cope rearrangement has been observed; *Mukai* [163]

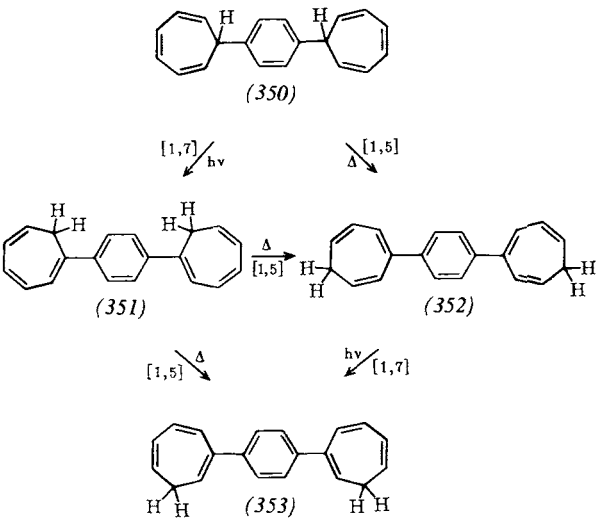


(347) (348) (349)

reported the stereospecific rearrangement of *(347)* to *(348)*. The case provides a striking instance of the manner in which framework restraints may operate to make otherwise difficultly accessible symmetry-allowed reactions possible [*cf.* the transition state *(349)*].

The antarafacial sigmatropic transformation of order [1,7] has been known for some time, in the precalciferol→calciferol interconversion [164].

In cycloheptatriene an antarafacial [1,7] shift is impossible. Consequently, [1,7] shifts within this system must be photochemically induced, or occur with inversion at the shifting site if thermal. A number of



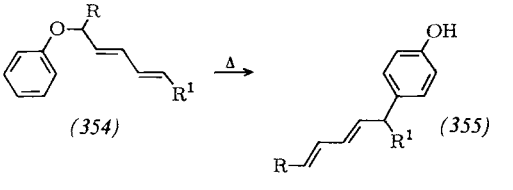
sequences of such light-induced [1,7] rearrangements have been observed [165].

Murray and *Kaplan* [166] have observed the consistent sequence *(350)–(353)* of thermal [1,5] and photochemical [1,7] sigmatropic hydrogen shifts among the isomers of 1,4-di(cycloheptatrienyl)benzene.

Further fascinating examples of [1,7] shifts have been described by *Schmid* [166a].

A symmetry-allowed [3,5] sigmatropic rearrangement must be an excited state reaction if constrained to be suprafacial on both components. So far, there appears to have been observed one case only [167].

The first [5,5] sigmatropic shift has now been realized by *Fráter* and *Schmid* [168], in the facile stereospecific rearrangement of *(354)* to *(355)*.



(354) (355)

[1,2] Shifts in a carbonium ion are very common [169]. Stereospecific hydrogen or methyl shifts in benzenonium cations [170] may be regarded as [1,2] or [1,6] shifts.

[162] *Cf. W. von E. Doering* and *W. R. Roth*, Tetrahedron *18*, 67 (1962); Angew. Chem. *75*, 27 (1963); Angew. Chem. internat. Edit. *2*, 115 (1963); *S. J. Rhoads* in *P. de Mayo:* Molecular Rearrangements. Interscience, New York 1963, Vol. 1, p. 655; *A. Jefferson* and *F. Scheinmann*, Quart. Rev. *22*, 391 (1968).

[163] *T. Miyashi, M. Nitta*, and *T. Mukai*, Tetrahedron Letters *1967*, 3433.

[164] *J. L. M. A. Schlatmann, J. Pot*, and *E. Havinga*, Rec. Trav. Chim. Pays-Bas *83*, 1173 (1964); *M. Akhtar* and *C. J. Gibbons*, Tetrahedron Letters *1965*, 509.

[165] *A. P. ter Borg* and *H. Kloosterziel*, Rec. Trav. Chim. Pays-Bas *84*, 241 (1965); *W. von E. Doering* and *P. P. Gaspar*, J. Amer. chem. Soc. *85*, 3043 (1963); *W. R. Roth*, Angew. Chem. *75*, 921 (1963); Angew. Chem. internat. Edit. *2*, 688 (1963); *L. B. Jones* and *V. K. Jones*, J. Amer. chem. Soc. *90*, 1540 (1968).

[166] *R. W. Murray* and *M. L. Kaplan*, J. Amer. chem. Soc. *88*, 3527 (1966).

[166a] *R. Hug, H.-J. Hansen*, and *H. Schmid*, Chimia *23*, 108 (1969).

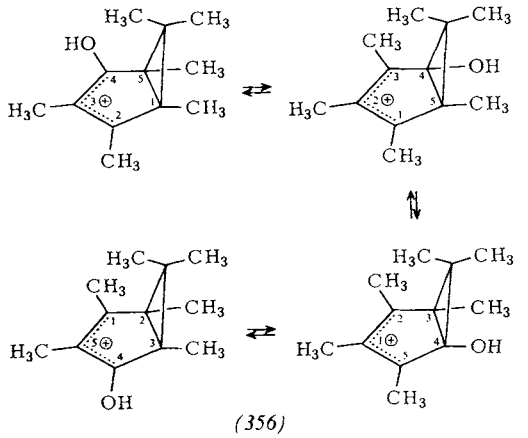
[167] *K. Schmid* and *H. Schmid*, Helv. chim. Acta *36*, 687 (1953).

[168] *Gy. Fráter* and *H. Schmid*, Helv. chim. Acta *51*, 190 (1968).

[169] *Cf.* the reviews by *Y. Pocker*, and by *J. A. Berson* in *P. de Mayo:* Molecular Rearrangements. Interscience, New York 1963, Vol. 1.

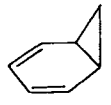
[170] *D. A. McCaulay* and *A. P. Lien*, J. Amer. chem. Soc. *79*, 5953 (1957); *H. Steinberg* and *F. L. J. Sixma*, Rec. Trav. Chim. Pays-Bas *81*, 185 (1962); *C. MacLean* and *E. L. Mackor*, J. chem. Physics *34*, 2208 (1961); *V. A. Koptyug, V. G. Shubin*, and *A. I. Rezvukhin*, Izv. Akad. Nauk SSSR *1965*, 201.

Sigmatropic reactions of order [1,4], *e.g.* migrations in a but-2-en-1-yl cation, have not been observed until recently, when *Swatton* and *Hart* reported the very rapid degenerate rearrangement *(356)* [171].



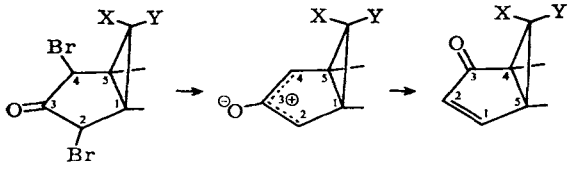
(356)

A [1,4] sigmatropic shift constrained to proceed suprafacially must take place with inversion at the migrating group. Note how this prediction contrasts with that for the [1,5] shift in the sterically very similar *(357)*.



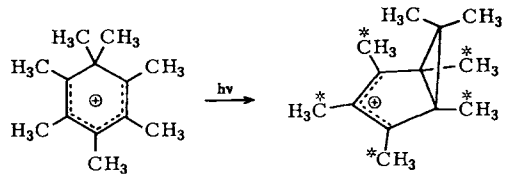
(357)

The predicted inversion in a [1,4] sigmatropic shift has recently been verified by several groups. *Hill* [172], and *Zimmerman* [173] have demonstrated that such a process occurs in the Favorskii reaction of a bicyclo-[3.1.0]hexanone [*(358)*→*(359)*→*(360)*].



(358) *(359)* *(360)*

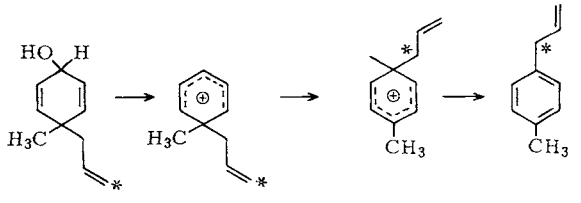
Further, *Hart* [174] has demonstrated that the rearrangement *(356)* previously discovered by him [171] indeed proceeds with inversion. The clearest demonstration of the nature of this rearrangement has been obtained by *Winstein* and *Childs* [175]. They generated various methylated bicyclo[3.1.0]hexenyl cations *(362)* in highly acidic media under conditions such that the nuclear magnetic resonance spectrum of the cation



(361) *(362)*

could be observed directly at various temperatures. The cations were generated by the symmetry-allowed photochemical disrotatory cyclization of the corresponding cyclohexadienyl cations *(361)* and were relatively stable, in consequence of the symmetry-imposed barrier to thermal reversion. As the temperature at which the measurements were made was raised, in the case of the heptamethyl compound *(362)* an averaging process took place; five methyl groups (marked by asterisks) became equivalent, while the other two methyl groups, which at low temperature gave distinct resonances, remained unaffected.

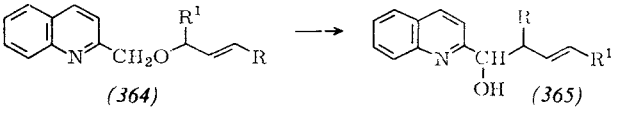
Several examples of [3,4] cationic sigmatropic reactions have recently become available through the elegant researches of *Schmid* [176]. In these dienol-ben-



(363)

zene, as well as the analogous dienone-phenol, rearrangements, the [3,4] sigmatropic reactions are competitive with equally allowed [1,2] and [3,3] shifts.

There also may be at hand some examples of [2,3] anionic sigmatropic reactions, in the Wittig rearrangement – the base-catalyzed transformation of benzyl ethers to alcohols. Thus, *Makisumi* and *Notzumoto* [177] observed the base-catalyzed conversion of *(364)* to *(365)*. Similar results on labeled 9-fluorenylallyl eth-



(364) *(365)*

ers were obtained by *Schöllkopf* [178]. The isoelectronic analogue [*(366)*→*(367)*], within formally neutral species, has been found to occur readily, and has been recognized as a very general reaction-type [179].

[171] *D. W. Swatton* and *H. Hart*, J. Amer. chem. Soc. *89*, 5075 (1967).

[172] *T. M. Brennan* and *R. K. Hill*, J. Amer. chem. Soc. *90*, 5614 (1968).

[173] *H. E. Zimmerman* and *D. S. Crumrine*, J. Amer. chem. Soc. *90*, 5612 (1968).

[174] *H. Hart, T. R. Rodgers*, and *J. Griffiths*, J. Amer. chem. Soc *91*, 754 (1969).

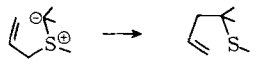
[175] *R. F. Childs* and *S. Winstein*, J. Amer. chem. Soc. *90*, 7146 (1968).

[176] *H.-J. Hansen, B. Sutter*, and *H. Schmid*, Helv. chim. Acta *51*, 828 (1968).

[177] *Y. Makisumi* and *S. Notzumoto*, Tetrahedron Letters *1967*, 6393.

[178] *U. Schöllkopf* and *K. Fellenberger*, Liebigs Ann. Chem. *698*, 80 (1966). See also *H. E. Zimmerman* in *P. de Mayo:* Molecular Rearrangements. Interscience, New York 1963, Vol. 1, p. 372.

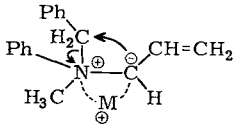
[179] *J. E. Baldwin, R. E. Hackler*, and *D. P. Kelly*, Chem. Commun. *1968*, 537, 538; *G. M. Blackburn, W. D. Ollis, J. D. Plackett, C. Smith*, and *I. O. Sutherland, ibid. 1968*, 186; *R. B. Bates* and *D. Feld*, Tetrahedron Letters *1968*, 417; *B. M. Trost* and *R. LaRochelle, ibid. 1968*, 3327; *J. E. Baldwin* and *R. E. Peavy, ibid. 1968*, 5029; *W. Kirmse* and *M. Kapps*, Chem. Ber. *101*, 994, 1004 (1968).



(366) (367)

We would expect that [1,2] anionic shifts should proceed with inversion at the migrating atom. Such shifts have been observed[180] in all-carbon systems, but stereochemical information is not available. The Stevens rearrangement involves the migration of an alkyl group from a quaternary ammonium atom to an adjacent carbanionoid center. The reaction is thus isoelectronic with a [1,2] carbanion rearrangement. It is definitely intramolecular[181], and migration proceeds with retention of configuration at the shifting carbon atom[182]. There is considerable argument concerning the mechanism of the reaction[180,182,183]. Ion-pair and diradical mechanisms have been suggested[182,183] which might circumvent the disagreement with the predictions for a concerted process.

The perhaps bizarre alternative suggestion may be put forward that the metal ions always associated with such systems play a determinative role. If a metal ion is strongly associated with the carbanionoid center at the outset of reaction, and with the nitrogen atom when the migration has been concluded, the symmetry-allowed process depicted in *(368)* may be envisaged; in



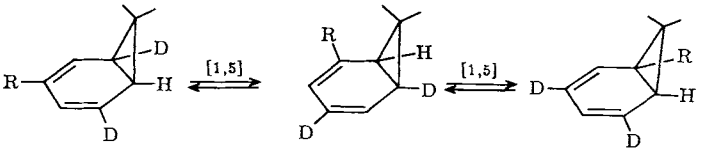
(368)

this change, inversion occurs at nitrogen and at the carbanionoid carbon, and a *p* orbital of the metal is involved.

(369)

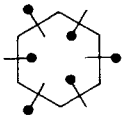
The homo [1,5] sigmatropic shift *(369)* is very well known[184].

The impetus for a general consideration of sequential sigmatropic shifts arose from the experimental observation by *Berson* and *Willcott* of a sequence of [1,5] sigmatropic shifts *(370)* in norcaradienes[161]. Such



(370)

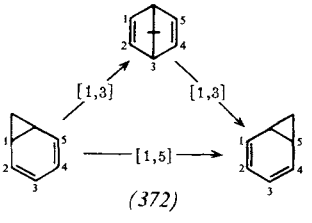
processes must proceed *with retention* at the migrating carbon atom. The consequences of a sequence of motions with retention are sketched in *(371)*. The illustration is essentially a superposition of snapshots of all of



(371)

the possible positions of labels attached to the methylene carbon atom as it migrates around the six-membered ring (*cf.* Figure 36).

Now it is also conceivable, though energetically unlikely, that the methylene group might migrate by a sequence of [1,3] sigmatropic shifts, through norbornadiene intermediates *(372)*.



(372)

In that connection the following question may be asked: given that suprafacial [1,5] sigmatropic shifts must proceed with retention, and that [1,3] shifts must proceed with inversion if constrained to be suprafacial – is it true that a random sequence of [1,3] and [1,5]

[180] *E. Grovenstein, jr.*, and *G. Wentworth*, J. Amer. chem. Soc. *89*, 1852, 2348 (1967), and references therein.

[181] *T. S. Stevens*, J. chem. Soc. *1930*, 2107; *R. A. W. Johnstone* and *T. S. Stevens*, ibid. *1955*, 4487. *R. K. Hill* and *T.-H. Chan*, J. Amer. chem. Soc. *88*, 866 (1966).

[182] *J. H. Brewster* and *M. W. Kline*, J. Amer. chem. Soc. *74*, 5179 (1952); *B. J. Millard* and *T. S. Stevens*, J. chem. Soc. *1963*, 3397; *E. F. Jenny* and *J. Druey*, Angew. Chem. *74*, 152 (1962); Angew. Chem. internat. Edit. *1*, 155 (1962).

[183] *D. J. Cram:* Fundamentals of Carbanion Chemistry. Academic Press, New York 1965, p. 223; *P. T. Lansbury, V. A. Pattison, J. D. Sidler*, and *J. B. Bieber*, J. Amer. chem. Soc. *88*, 78 (1966); *A. R. Lepley, ibid. 91*, 1237 (1969); *J. E. Baldwin*, personal communication.

[184] *D. S. Glass, J. Zirner*, and *S. Winstein*, Proc. chem. Soc. *1963*, 276; *R. J. Ellis* and *H. M. Frey, ibid. 1964*, 221; J. chem. Soc. *1964*, Suppl. 1, 5578; *W. R. Roth*. Liebigs Ann. Chem. *671*, 10 (1964); *W. R. Roth* and *J. König, ibid. 688*, 28 (1965); *W. Grimme*, Chem. Ber. *98*, 756 (1965); *J. K. Crandall* and *R. J. Watkins*, Tetrahedron Letters *1967*, 1717; *R. M. Roberts, R. G. Landolt, R. N. Greene*, and *E. W. Heyer*, J. Amer. chem. Soc. *89*, 1404 (1967); *G. Ohloff*, Tetrahedron Letters *1965*, 3795; *W. R. Roth*, Chimia *20*, 229 (1966). – The reaction is also known in the case of cyclopropyl-carbonyl compounds: *D. E. McGreer, N. W. K. Chiu*, and *R. S. McDaniel*, Proc. chem. Soc. *1964*, 415. A special case of some interest is the "abnormal Claisen rearrangement" studied by *E. N. Marvell, D. R. Anderson*, and *J. Ong*, J. org. Chem. *27*, 1109 (1962); *W. M. Lauer* and *T. A. Johnson, ibid. 28*, 2913 (1963); *A. Habich, R. Barner, W. von Philipsborn*, and *H. Schmid*, Helv. chim. Acta *48*, 1297 (1964); *R. M. Roberts* and *R. G. Landolt*, J. Amer. chem. Soc. *87*, 2281 (1965); *R. M. Roberts, R. N. Greene, R. G. Landolt*, and *E. W. Heyer, ibid. 87*, 2282 (1965); *R. M. Roberts, R. G. Landolt, R. N. Greene*, and *E. W. Heyer, ibid. 89*, 1404 (1967). See also *J. M. Conia, F. Leyendecker*, and *C. Dubois-Faget*, Tetrahedron Letters *1966*, 129; *F. Rouessac* and *J. M. Conia, ibid. 1965*, 3313.

shifts will produce only the same labeling pattern as the previously analyzed sequence of [1,5] shifts [*cf. (371)*]? In this case the answer is yes, as shown by a diagram

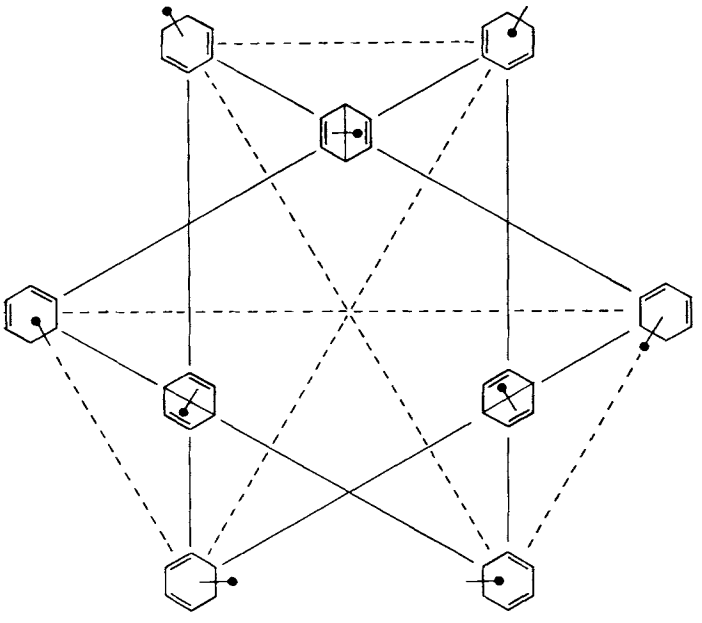
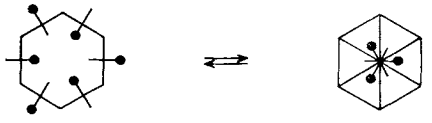


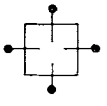
Figure 37. Sigmatropic [1,3] and [1,5] shifts in substituted norcaradienes and norbornadienes. — [1,3] shifts, ···· [1,5] shifts.

(Figure 37) relating all the possible species through all the possible paths. The information contained in Figure 37 is summarized in *(373)* and *(374)*.



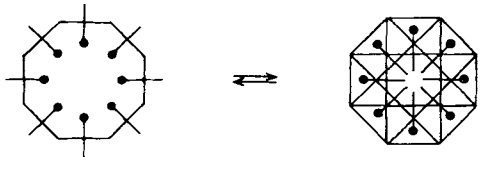
(373) *(374)*

Similar questions may be posed for other [2n.1.0] bicyclic systems. For the [2.1.0] system, only [1,3] shifts are possible; the labeling pattern is summarized in *(375)*.



(375)

For the [6.1.0] system [1,3], [1,5], and [1,7] shifts are all possible. The diagram relating all isomers is very complicated, but its information content may be summarized in *(376)* and *(377)*. Here again any sequence of [1,3], [1,5], or [1,7] shifts which relates two isomers gives the same configuration as any other sequence.



(376) *(377)*

It may be shown that the results derived above represent a general topological property of [2n.1.0] bicyclic systems.

There are two parts to the proof. First, it is clear that a [1,5] shift with retention at a migrating center is indistinguishable from a sequence of *two* [1,3] shifts, each proceeding with inversion at the migrating center. Similarly, a [1,7] shift with inversion is stereochemically indistinguishable from a series of *three* [1,3] shifts, each with inversion. In general,

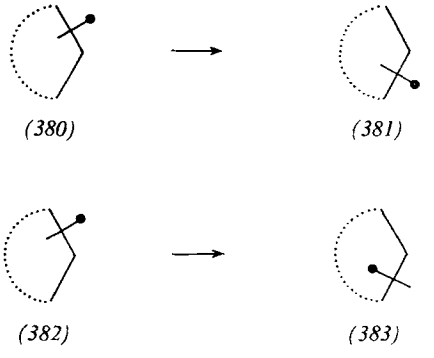
$$[1, (2q+1)] = [1,3]^q$$

Consequently, it is sufficient to consider a random sequence of [1,3] shifts in constructing a proof.

We will prove that in a bicyclo[(2n−2).1.0] system *every* possible sequence of [1,3] shifts which effects the transformation of *(378)* into *(379)* contains an odd number

(378) *(379)*

of such shifts if n is even, and an even number of shifts if n is odd. Thus, it will be shown that for n even, there is an odd number of inversions, *i. e.* one net inversion [*(380)*→*(381)*], whereas for n odd, there is net retention [*(382)*→*(383)*]. The cyclic symmetry of the rearrangement then generates the isomer relationships shown in *(384)*.



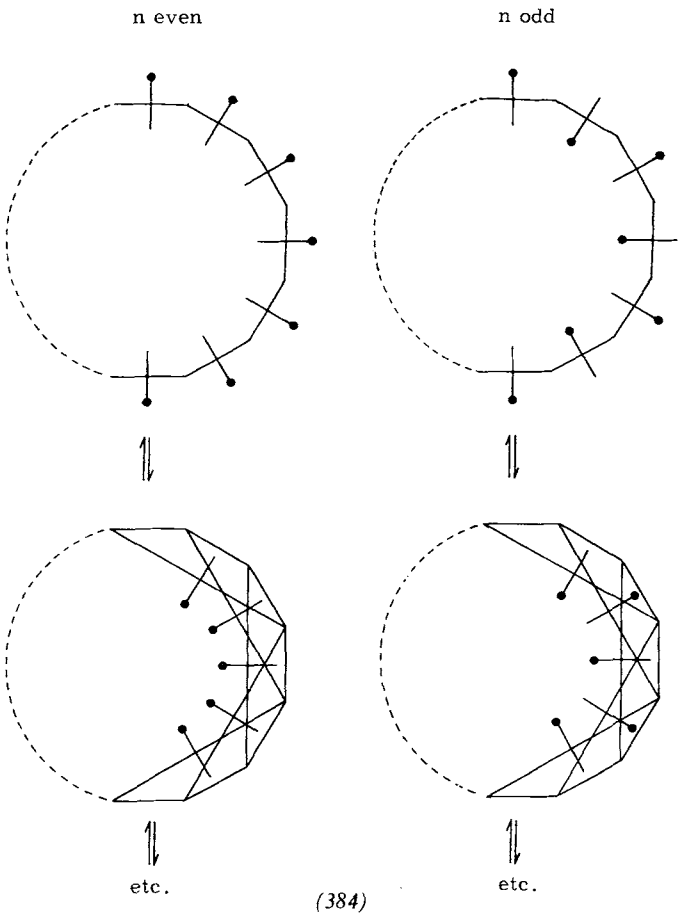
(380) *(381)*

(382) *(383)*

We now construct the mathematical problem equivalent to the rearrangement sequence. Consider a polygon *(385)* with $2n$ vertices, numbered sequentially clockwise from an arbitrary origin. Suppose markers, A and B, are placed at vertices 1 and 2, respectively, of this polygon. A game is then played, with the following set of rules:

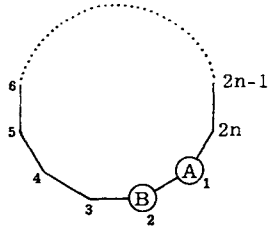
a) A random number of moves of the markers to new vertices is performed sequentially.

b) In each move *either* A *or* B moves two positions clockwise or counterclockwise. Thus, if A is at position k, it can move to $k+2$ or $k-2$.



(384)

c) No hopping is allowed; *i.e.* if A is located at point k and B at $k-1$, the move of A from k to $k-2$ is forbidden and A has only the option of moving to $k+2$.



(385)

Theorem: Given the above rules of the game, *every possible sequence of moves* which begins with A at 1 and B at 2 and terminates with A at 3 and B at 2 comprises an even number of moves if n is odd, and an odd number of moves if n is even.

Before proceeding to the proof of this theorem, one should assure oneself that the above game and theorem are equivalent to the problem presented by the sequential rearrangements. The requisite identifications are that the ring of $2n$ atoms, around which the carbon atom moves, corresponds to the polygon, while the markers A and B represent the bonds from the vertices of the polygon to the migrating atom.

Proof: Define a distance, measured in number of sides of the polygon, between the markers A and B, beginning at B, and *measured clockwise*. Then if B is at 2 and A is at 1, the distance between the two is the maximum: $2n-1$. We now proceed to examine the number of steps it takes to reduce this distance between the markers to 1, with B at 2 and A at 3. First, we will examine the number of moves it takes to reduce the distance to 1, *when B may have moved to any vertex*. The initial move reduces the distance from $2n-1$ to $2n-3$. Every subsequent move can be classified as *effectual* or *ineffectual*. An effectual move makes the distance smaller than the previous minimum, an ineffectual move does not. All ineffectual moves come in pairs: for, if at some point the distance is j, and a move increases the distance to $j+2$, then another move is necessary to return it to j. Only effectual moves reduce the distance between A and B. Since each effectual move reduces the distance by 2, the total number of moves, for any sequence, necessary to reduce the distance from $2n-1$ to 1 is:

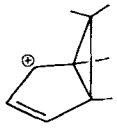
$$(2n-2)/2 = (n-1) + \text{some even number}$$
Effectual *Ineffectual*

So far we have deduced the number of moves necessary to reduce the distance to 1, but B may be at any even-numbered vertex. Now, A and B having been placed at *any* adjacent vertices, an even number of ineffectual moves will suffice to realize the final objective of placing B at position 2, and A at position 3. We have thus shown that the total number of necessary moves is:

$$(n-1) + \text{some even number}$$

Consequently, the required number of moves is odd if n is even, and even if n is odd, which was to be proven.

For cationic sigmatropic rearrangements, the topological relationships can differ significantly from those just shown to be general for neutral species. We consider first the sigmatropic rearrangements of a bicyclo[3.1.0]hexenyl cation *(386)*. In this system [1,2],



(386)

[1,4], and [1,3] shifts may occur; experience indicates that ionic [1,2q] shifts should be much faster than the neutral [1,(2q+1)] rearrangements. Using the previous conventions, and observing the symmetry-imposed conditions that [1,2] shifts must occur with retention, while [1,3] and [1,4] migrations must take place with inversion, we obtain the interrelations shown in Figure 38. The relationships are summarized in *(387)* and *(388)*.

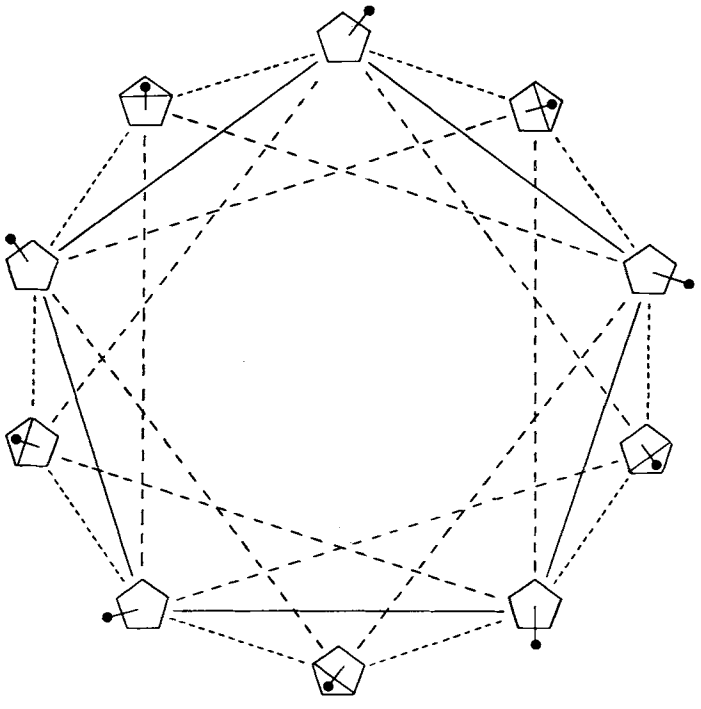
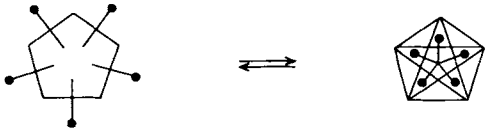


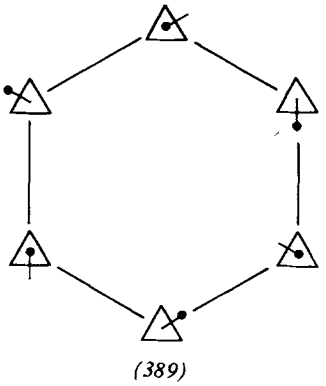
Figure 38. Sigmatropic [1,4], [1,2], and [1,3] shifts in the cation *(386)*. — [1,4] shifts, ····· [1,2] shifts, --- [1,3] shifts.

At this point it might appear that sequential sigmatropic reactions in cyclic polyenyl ions will always have the same consequences as in cyclic polyenes. *This is not*



(387) *(388)*

so. Consider the simplest system in which [1,2] shifts are possible – the rearrangements of the bicyclo-[1.1.0]butyl cation *(389)*. In sharp contrast to those in



(389)

each of the previous cases studied, this sequence produces apparent epimerization, *i.e.* a series of rearrangements can convert *(390)* into *(391)*. It may be readily

(390) *(391)*

seen that similar circumstances will obtain in (7, 11, ...)-membered rings – as well as in the three-membered case (*cf.* Figure 39).

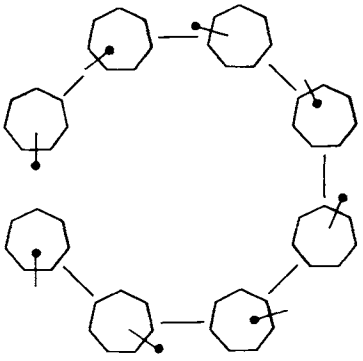
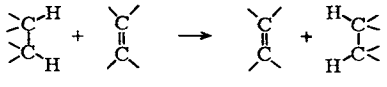


Figure 39. [1,6] Sigmatropic shifts in bicyclo[5.1.0]octadienyl cations.

The bicyclo[(2n+1).1.0] cation cases thus must be divided into two categories. In the first class, the [1,(2n+2)] sigmatropic shift proceeds with *retention* and epimerization must occur as a consequence of $2n+3$ such shifts; such is the case for [1,2], [1,6], [1,10], ... shifts, that is, in general for cases where n is even. The second category comprises those cases in which n is odd, the [1,(2n+2)] sigmatropic shift proceeds with *inversion*, and epimerization can never be realized through any number of symmetry-allowed migrations – as in the cyclic polyene cases.

8. Group Transfers and Eliminations

Consider the concerted reaction in which two hydrogen atoms are transferred from ethane to ethylene *(392)*, in a process suprafacial on both reactants. A



(392)

correlation diagram (Figure 40) is easily constructed for this reaction, utilizing the symmetry plane bisecting the two molecules; the process is clearly symmetry-allowed. In contrast is the diagram (Figure 41) for the

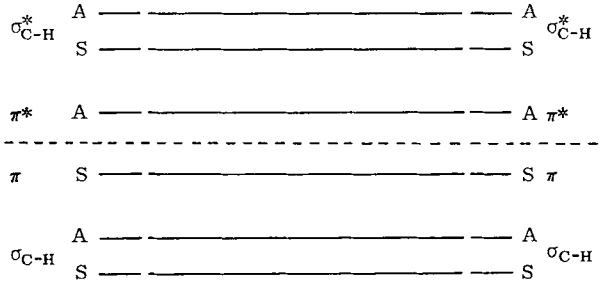
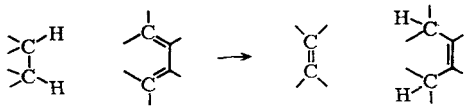


Figure 40. Correlation diagram for the concerted transfer of two hydrogen atoms from ethane to ethylene.



(393)

concerted transfer of two hydrogen atoms from ethane to the termini of butadiene *(393)*; the reaction is symmetry-forbidden.

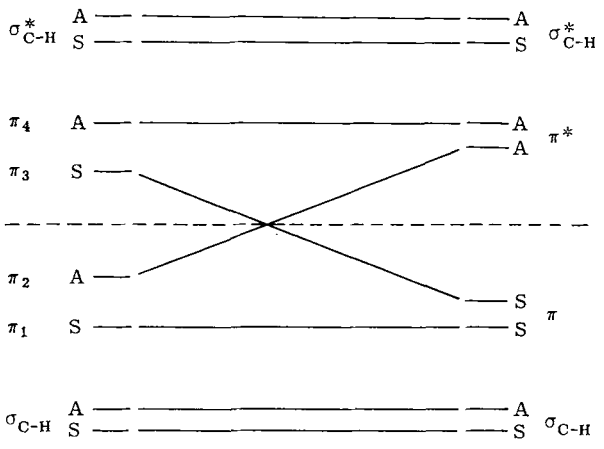
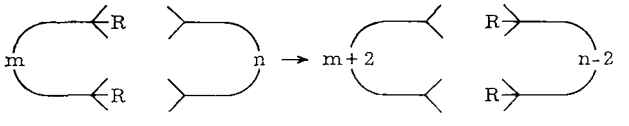


Figure 41. Correlation diagram for the concerted transfer of two hydrogen atoms from ethane to the termini of butadiene.

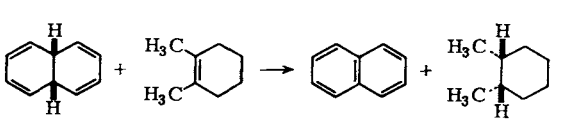
For the general case *(394)*, it is simple to derive the following selection rule: The double-group transfer is symmetry-allowed for ground states when



(394)

$m+n = 4q+2$, for excited states when $m+n = 4q$, where m and n are numbers of π electrons, and q is an integer (0, 1, 2, . . .). The rule applies also to a process antarafacial on both components, and is reversed for a process antarafacial on one component only. The rules must be appropriately modified if the possibility of inversion at R is real (*cf.* Section 11).

The best known example of this type of reaction, with $m = 0$, $n = 2$, is the transfer of hydrogen from diimide to olefins [185]. Hydrocarbon analogues also exist; for example, the reaction *(395)* was observed by *Doering* and



(395)

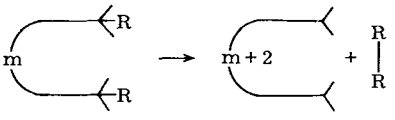
[185] Reviewed by *S. Hünig, H. R. Müller*, and *W. Thier*, Angew. Chem. *77*, 368 (1965); Angew. Chem. internat. Edit. *4*, 271 (1965); *E. J. Corey, D. J. Pasto*, and *W. L. Mock*, J. Amer. chem. Soc. *83*, 2957 (1961).

[186] *W. von E. Doering* and *J. W. Rosenthal*, J. Amer. chem. Soc. *89*, 4535 (1967).

Rosenthal [186]. A case with $m = 2$, $n = 4$ has also been observed *(396)* [187].

(396)

The rule derived above also applies to the limiting case with $n = 0$ – the concerted elimination *(397)*. We predicted, thus, that the concerted noncatalytic hydrogenation of a diene, or the reverse elimination, should be



(397)

1,4 rather than 1,2. At the time our predictions were made the literature appeared to contain only two relevant pieces of information:

a) 2,5-Dihydrofuran loses hydrogen in a unimolecular process with $E_a = 48.5$ kcal/mole and a negative entropy of activation, while 2,3-dihydrofuran does not react in this way [188].

b) 3,3,6,6-Tetramethyl-1,4-cyclohexadiene when pyrolyzed in pentane gave a much larger yield of ethane (and *p*-xylene) than could have arisen from a free radical chain reaction [189].

Subsequently, our predictions have been substantiated in a number of studies. *Baldwin* [190] in studying the elimination of hydrogen from an isotopically labeled cyclopentene found a greater than 10:1 preference for 1,4 over 1,2 elimination. *Ellis* and *Frey* [191], *Benson* and *Shaw* [192], and *Kellner* and co-workers [193] have independently studied the pyrolysis of 1,3 and of 1,4-cyclohexadiene. The latter decomposes unimolecularly to benzene and hydrogen with $E_a = 42.7$ kcal/mole; at the same temperatures the 1,3-cyclohexadiene is thermally stable and at higher temperatures it decomposes mainly by radical-chain processes. *Frey* has provided further interesting examples of concerted elimination of hydrogen; on the other hand, his evidence indicates that those processes which lead to the formation of methane or ethane proceed by radical-chain mechanisms [194].

[187] *P. Dowd*, personal communication; *I. Fleming*, personal communication.

[188] *C. A. Wellington* and *W. D. Walters*, J. Amer. chem. Soc. *83*, 4888 (1961).

[189] *W. Reusch, M. Russell*, and *C. Dzurella*, J. org. Chem. *29*, 2446 (1964).

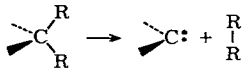
[190] *J. E. Baldwin*, Tetrahedron Letters *1966*, 2953.

[191] *R. J. Ellis* and *H. M. Frey*, J. chem. Soc. *A*, *1966*, 553.

[192] *S. W. Benson* and *R. Shaw*, Trans. Faraday Soc. *63*, 985 (1967); J. Amer. chem. Soc. *89*, 5351 (1967).

[193] *W. D. Walters*, personal communication.

[194] *H. M. Frey* and *D. H. Lister*, J. chem. Soc. *A*, *1967*, 509, 1800; *H. M. Frey* and *R. Walsh*, Chem. Rev. *69*, 103 (1969).



(398)

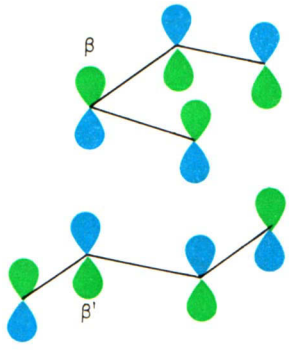
The concerted loss of two geminal groups *(398)*, provided that it proceeds through a transition state of C_{2v} symmetry (*cf.* Section 10.1), should be an excited state reaction, and thus compete with vicinal elimination [*(397)*, $m=0$] – also a symmetry-allowed excited state process. Both cases are known [195].

9. Secondary Effects

Orbital symmetry arguments may also be used to yield further insight into the origins of secondary conformational effects in concerted cycloaddition reactions.

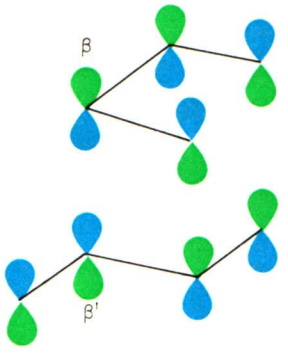
Consider the Diels-Alder addition of butadiene to itself, as a concerted $[\pi 4_s+\pi 2_s]$ cycloaddition reaction. *A priori*, this reaction might take place through either of two alternative transition states, *(399)* or *(400)*. The *endo* approach *(399)* is distinguished from the *exo* *(400)* mainly by the proximity of a β and a β′ orbital in the former. Any secondary interaction among occupied diene and dienophile molecular orbitals will contribute only in a very minor way to the total energy of the transition state, since such an interaction will increase the energy of some levels while decreasing the energy of others. The significant interactions will come from the symmetry-allowed mixing of unoccupied with occupied levels [196]. In the case at hand, inspection of diagrams *(401)* and *(402)* reveals at once that either possibility for such mixing leads to bonding, *i.e.* energy-lowering, interaction of the proximate β and β′ orbitals [197]. Thus, the *endo* transition state *(399)* for this $[\pi 4_s+\pi 2_s]$ concerted cycloaddition reaction is stabilized *vis-à-vis* the *exo* alternative *(400)* by symmetry-controlled secondary orbital interactions.

The orbital symmetry relationships signalized here provide a simple quantum chemical basis for the large body of experience summarized in the Alder *endo* addition rule [198]. Our treatment differs from previous proposals, which have emphasized the roles of inductive



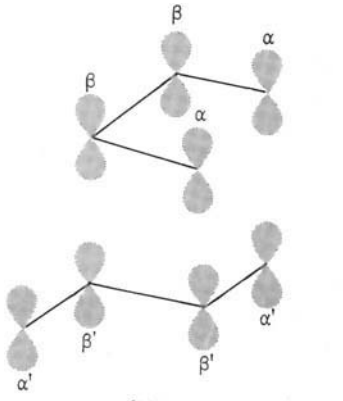
(401)

Mixing of highest occupied "diene" orbital (top) with lowest unoccupied "olefin" orbital (bottom)

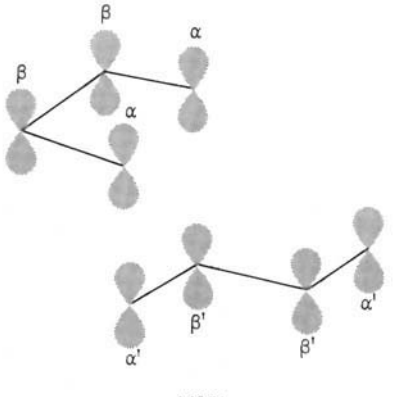


(402)

Mixing of lowest unoccupied "diene" orbital (top) with highest occupied "olefin" orbital (bottom)



(399)



(400)

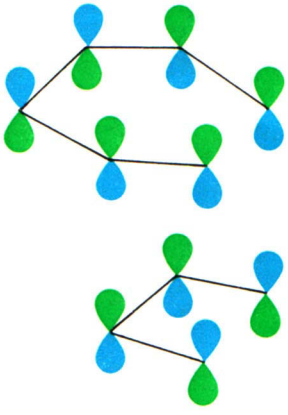
[195] Photolysis of cyclohexadiene: *R. Srinivasan*, J. Amer. chem. Soc. *83*, 2806 (1961); photolysis of ethane and ethylene: *M. Okabe* and *J. R. McNesby*, J. chem. Physics *34*, 668 (1962); cyclohexane: *R. P. Doepker* and *P. Ausloos*, *ibid. 42*, 3746 (1965). In the gas phase photolysis of azomethane, it is well established that the predominant primary process is decomposition to nitrogen and two methyl radicals; however, some evidence has been presented for a minor molecular elimination of ethane: *R. E. Rebbert* and *P. Ausloos*, J. phys. Chem. *66*, 2253 (1962).

[196] This has also been stressed by *K. Fukui* in *P.-O. Löwdin* and *B. Pullman:* Molecular Orbitals in Chemistry, Physics, and Biology. Academic Press, New York 1964, p. 525.

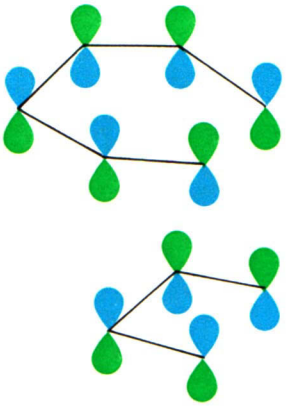
[197] The role of other secondary interactions has been stressed by *L. Salem*, J. Amer. chem. Soc. *90*, 543, 553 (1968).

[198] *K. Alder* and *G. Stein*, Angew. Chem. *50*, 514 (1937); *K. Alder*, Liebigs Ann. Chem. *571*, 157 (1951); *K. Alder* and *M. Schumacher*, Fortschr. Chem. org. Naturstoffe *10*, 1 (1953). For exceptions to the rule, *cf. J. A. Berson*, *Z. Hamlet*, and *W. A. Mueller*, J. Amer. chem. Soc. *84*, 297 (1962).

forces [199], electrostatic forces consequent upon charge transfer between diene and dienophile [200], and maximum accumulation of unsaturation [198]. In particular it is now clear that in some cases the orbital interactions among unsaturated centers involved in a concerted cycloaddition reaction will be such as to raise rather than lower, the energy of the *endo* transition state, and lead to a preference for *exo* addition, insofar as



(403)

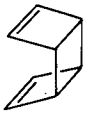


(404)

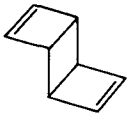
symmetry factors are dominant; inspection of the relevant orbital diagrams *(403)* and *(404)* for the symmetry-allowed $[\pi 6_s+\pi 4_s]$ combinations indicates that it is such a case.

This prediction was made prior to the discovery of [6+4] cycloadditions, and has since been confirmed [201]. By contrast, the symmetry-allowed $[\pi 8_s+\pi 2_s]$ and $[\pi 2_s+\pi 2_s+\pi 2_s]$ cycloadditions should resemble the [4+2] process and proceed by preference through *endo* transition states; there is already evidence for that preference in an example of the latter process [202].

The dimerization of cyclobutadiene is a special case of much interest, considered in the light of orbital symmetry relationships. If, as seems likely, there is substantial double bond localization in that highly reactive molecule, one can delineate, *a priori*, the possibilities of $[\pi 2_s+\pi 2_s]$, $[\pi 2_s+\pi 4_s]$, and $[\pi 4_s+\pi 4_s]$ cycloadditions. Our selection rules require a preference for the concerted $[\pi 2_s+\pi 4_s]$ process, and indeed evidence that this path is favored has been brought forward [203]. Examination



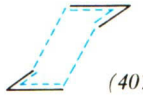
(405)



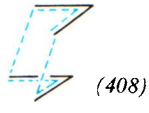
(406)

of secondary orbital interactions along the lines set down here reveals further that the *endo* process, leading to the *syn* dimer *(405)*, should be favored over the alternative *exo* combination, which would give the *anti* dimer *(406)*. The formation of both *syn* and *anti* dimers in reactions initiated with a variety of possible cyclobutadiene precursors has been reported, but in those experiments in which there was the greatest likelihood of the transitory existence of a free cyclobutadiene, the predicted *endo* process was observed [204].

The [3,3] sigmatropic shift in 1,5-hexadienes has been shown to proceed more easily through a four-center



(407)



(408)

chair-like transition state *(407)* than through the boat-like alternative *(408)* [205]. We suggest that orbital symmetry relationships may play a major role in determining that preference. A correlation diagram for the molecular orbitals involved in the rearrangement is illustrated in Figure 42. The levels are classified as symmetric or antisymmetric with respect to the mirror plane *m* in the boat-like transition state, or a two-fold rotation axis in the chair-like form. The scheme shown is for the former case, and the diagram for the latter is qualitatively similar. The correlation of reactant bonding levels with product bonding levels, characteristic of a symmetry-allowed thermal reaction, should be noted. At the half-way mark in the reaction the level ordering is recognizable as that of two strongly interacting allyl radicals. The actual behavior of the levels along the

[199] *A. Wassermann*, J. chem. Soc. *1935*, 825, 1511; *1936*, 432; Trans. Faraday Soc. *35*, 841 (1939).

[200] *R. B. Woodward* and *H. Baer*, J. Amer. chem. Soc. *66*, 645 (1944).

[201] *R. C. Cookson, B. V. Drake, J. Hudec*, and *A. Morrison*, Chem. Commun. *1966*, 15; *K. Houk*, Dissertation, Harvard (1968).

[202] *R. C. Cookson, J. Dance*, and *J. Hudec*, J. chem. Soc. *1964*, 5416.

[203] *G. Wittig* and *J. Weinlich*, Chem. Ber. *98*, 471 (1965).

[204] *R. Criegee*, Angew. Chem. *74*, 703 (1962); Angew. Chem. internat. Edit. *1*, 519 (1962), and references therein: *P. S. Skell* and *R. J. Peterson*, J. Amer. chem. Soc. *86*, 2530 (1964), and references therein; *L. Watts, J. D. Fitzpatrick*, and *R. Pettit*, *ibid. 88*, 623 (1966); *E. Hedaya, R. D. Miller, D. W. McNeil, P. F. D'Angelo*, and *P. Schissel*, J. Amer. chem. Soc. *91*, 1875 (1969).

[205] *W. von E. Doering* and *W. R. Roth*, Tetrahedron *18*, 67 (1962); Angew. Chem. *75*, 27 (1963); Angew. Chem. internat. Edit. *2*, 115 (1963); *R. K. Hill* and *N. W. Gilman*, Chem. Commun. *1967*, 619; for some recent theoretical work see *M. Simonetta, G. Favini, C. Mariani*, and *P. Gramaccioni*, J. Amer. chem. Soc. *90*, 1280 (1968). Similar preferences in the aromatic Claisen rearrangement have been elegantly studied by *Gy. Fráter, A. Habich, H.-J. Hansen*, and *H. Schmid*, Helv. chim. Acta *52*, 335 (1969).

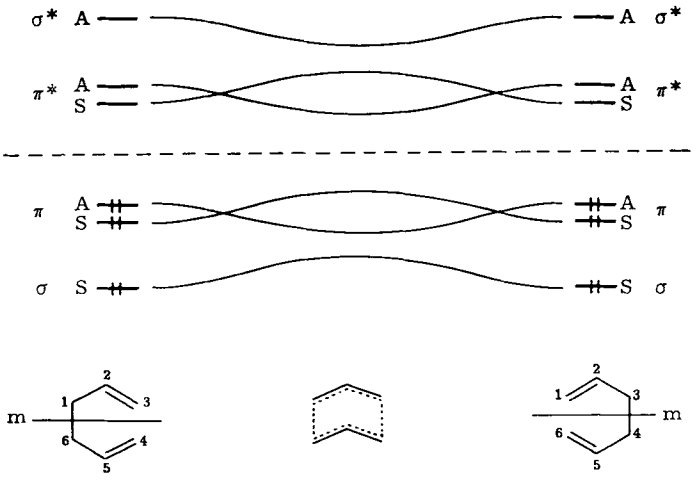


Figure 42. Correlation diagram for the [3,3] sigmatropic rearrangement of 1,5-hexadiene.

reaction coordinate is abstracted from extended Hückel calculations.

If the correlation diagrams are qualitatively similar for the boat and chair reactions, where does the observed preference come from? An explanation requires the construction of two further correlation diagrams (Figure 43), for the alternative hypothetical processes in which two allyl radicals approach each other from infinity, in parallel planes, oriented with respect to each other in the one case in a *quasi* boat relationship, and

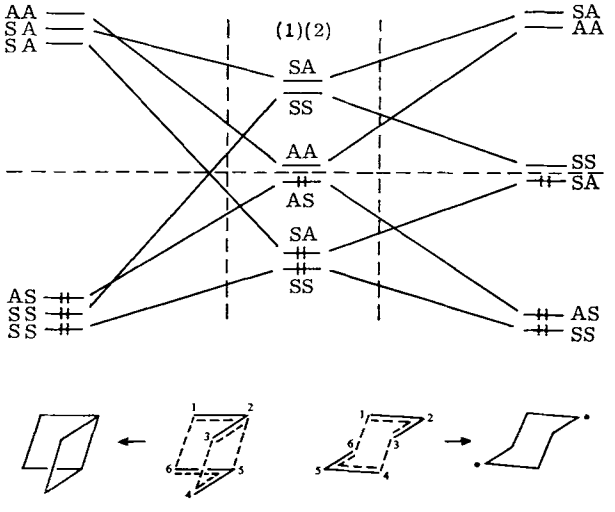


Figure 43. Correlation diagram for the approach of two allyl radicals from infinity in a *quasi* boat or a *quasi* chair relationship. (1) and (2) at the top of the center column refer to the symmetry elements present (see text).

in the other in a *quasi* chair fashion. In each of these processes there are two symmetry elements:

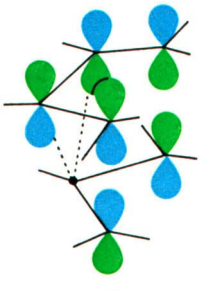
a) in both, a mirror plane m_1, which passes through C-2 and C-5, and bisects the angles C(1)-C(2)-C(3) and C(6)-C(5)-C(4);

b) in the boat approach, a second mirror plane, m_2, parallel to and half-way between the planes of the approaching radicals, and in the chair approach a two-fold axis of symmetry, lying on the intersection of m_2 and the plane defined by C(1)-C(3)-C(4)-C(6).

To complete the correlations one must specify the end products of these hypothetical motions; these are a bicyclohexane in the boat approach, and a 1,4-cyclohexylidene biradical in the chair pathway. Among the occupied levels the critical difference in the two pathways is in the behavior of the occupied S_1A_2 level, which in the boat-like approach correlates to an antibonding σ orbital while in the chair-like process it goes over to a non-bonding biradical level. The crucial point of the argument now is that a reaction proceeding as in Figure 42 must pass at the half-way point through some point in a correlation diagram resembling one or the other of those shown in Figure 43, and that this point will be approximately the same horizontal distance, marked by dashed vertical lines, along the reaction coordinate in the two alternate pathways of Figure 43. Further, at any such point the chair-like transition state is at lower energy as a result of the difference in correlation properties of the occupied S_1A_2 orbital. The central conclusion is that orbital interactions involving C-2 and C-5 have a net antibonding, energy-raising effect. In this sense, the argument represents a further development of the simple orbital repulsion effect suggested by *Doering* and *Berry* [205].

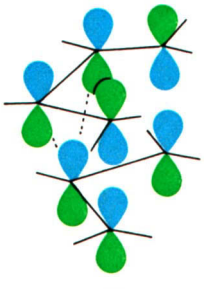
It should be emphasized that the effects discussed here are, not unexpectedly, small ones, and that in systems possessing special geometrical restraints which necessitate a boat-like transition state, [3,3] sigmatropic changes take place with no special difficulty [206].

To present a final illustration of the procedure, in a case in which the result is not yet known, we consider the [4+2] cycloaddition of a butadiene to an allyl cation. The two significant interactions are shown in *(409)* and *(410)*. The secondary interactions in *(409)* must be negligible, while those in *(410)* are antibonding; a preference for the *exo* transition state is expected [206a].



(409)

Mixing of highest occupied diene orbital (top) with lowest unoccupied allyl orbital (bottom)



(410)

Mixing of lowest unoccupied diene orbital (top) with highest occupied allyl orbital (bottom)

[206] *J. M. Brown*, Proc. chem. Soc. *1965*, 226; *W. von E. Doering* and *W. R. Roth*, Tetrahedron *19*, 715 (1963); *R. Merényi*, *J. F. M. Oth*, and *G. Schröder*, Chem. Ber. *97*, 3150 (1964); *H. A. Staab* and *F. Vögtle*, Tetrahedron Letters *1965*, 54.

[206a] Since the above was written, the prediction has been confirmed: *H. M. R. Hoffmann* and *D. R. Joy*, J. chem. Soc. *B 1968*, 1182.

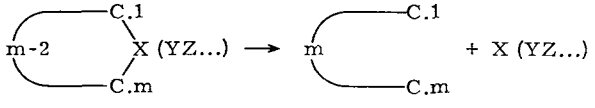
10. Divertissements!

In the previous sections, we have discussed and exemplified orbital symmetry control of the major general types of concerted organic reactions. We turn now to a discussion of two special types, each of which possesses fascinating unique features, and further illustrates the power of the principle of orbital symmetry conservation in understanding and predicting the detailed course of chemical transformations.

10.1. Cheletropic Reactions

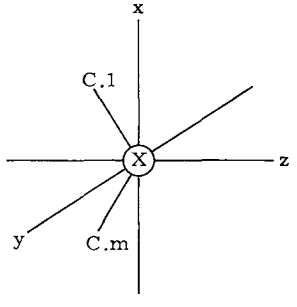
We define as *cheletropic reactions* those processes in which two σ bonds which terminate at a single atom are made, or broken, in concert.

Let us consider the cheletropic reaction *(411)*, in which a small molecule X(YZ. . .) and a polyene containing



(411)

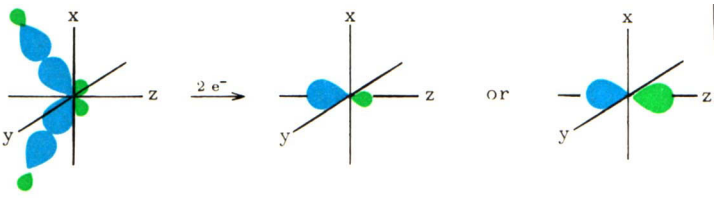
an *m*-electron π system are produced. We shall examine the geometrical aspects of the reaction, with reference to an invariant coordinate system *(412)*, whose origin is always at X, and whose z axis bisects the line



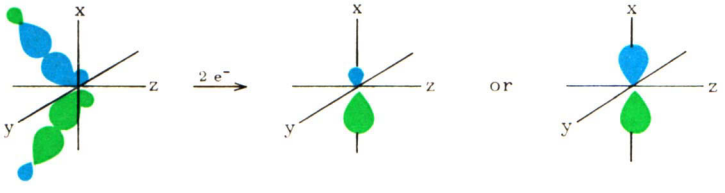
(412)

between C.1 and C.m. Thus, the σ bonds being broken lie in the xz plane, and their four electrons are distributed as usual, in pairs, in the two generalized orbitals *(413)* and *(414)*. Now, in general, two electrons must be delivered from these orbitals to each of the developing products, with conservation of orbital symmetry. A crucial point now emerges: the transfer of two electrons from the breaking σ bonds to new orbitals in the product molecule X(YZ. . .) may take place in either of two sharply distinct ways.

a) Two electrons from the symmetric orbital [*(413)* ≡*(415)*] may take up new positions in a z-symmetric lone pair orbital of X(YZ. . .), or enter a π system antisymmetric with respect to the xy plane.



(415)

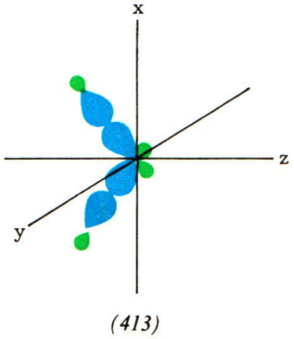


(416)

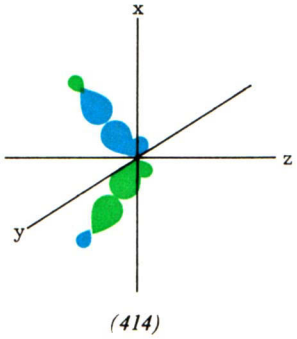
b) Two electrons from the antisymmetric orbital [*(414)* ≡*(416)*] may take up new positions in an x-symmetric lone pair orbital of X(YZ. . .), or enter a π system antisymmetric with respect to the yz plane.

In the light of this analysis, it is clear that the geometrical displacements at C.1 and C.m are dependent upon the detailed geometry of departure of X(YZ. . .), and in particular, on the sense of the displacements of the atoms YZ. . . which are attached to X. To illustrate this important point, we consider the departure of a bent molecule Y-X-Z, which as it develops must acquire a symmetric lone pair at the central atom X. The reaction may take place in either of two ways, depicted in *(417)* and *(418)*.

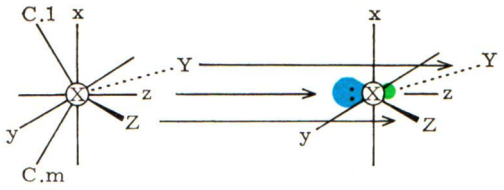
a) *Cf. (417)*: X acquires its needed lone pair from the symmetric σ orbital *(415)*, as X, Y, and Z depart co-lin-



(413)

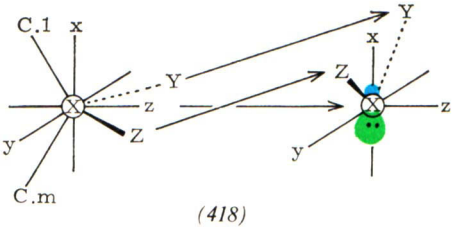


(414)



(417)

early, all remaining in the yz plane. We shall designate such processes as *linear* cheletropic reactions. It



(418)

may be noted that in a formal sense, the product electron pair is participating in a *suprafacial* fashion, in that the two bonds from which the two electrons came lie on the same side of the nodal surface (approximated by the plane xy) of the product orbital which the pair occupies.

b) *Cf. (418)*: X acquires its needed lone pair from the antisymmetric σ orbital *(416)*, as X departs co-linearly, remaining in the yz plane, while Y and Z undergo displacements in both the x and z directions, with the result that the product molecule lies in the xy plane. We shall designate such processes as *non-linear* cheletropic reactions. In this case the product electron pair at X is participating in an *antarafacial* fashion, in that the two bonds from which the electrons came lie on opposite sides of the nodal surface (approximated by the plane yz) of the product orbital which the pair occupies.

It is now clear that in linear cheletropic reactions of the type *(411)*, two electrons must be delivered from the antisymmetric σ orbital [*(416)* ≡*(420)* ≡*(423)*] to the highest occupied π orbital of the polyene *(419)*. Consequently, the displacements at C.1 and C.m must be disrotatory when $m=4q$ [*(420)*→*(421)*], and conrotatory when $m=4q+2$ [*(423)*→*(424)*].

By contrast, if the fragmentation *(411)* follows the non-linear cheletropic path, two electrons must be delivered to the highest occupied π orbital of the polyene *(419)* from the symmetric σ orbital [*(415)* ≡*(422)* ≡*(425)*]. In this case, therefore, the displacements at C.1 and C.m must be conrotatory if $m=4q$ [*(422)*→*(421)*], and disrotatory when $m=4q+2$ [*(425)*→*(424)*].

The selection rules are summarized in Figure 44. In these cheletropic transformations there undoubtedly

	Allowed Ground State Reactions	
m	Linear	Non-linear
4*q*	Disrotatory	Conrotatory
4*q*+2	Conrotatory	Disrotatory

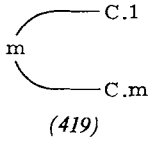
Figure 44. Selection rules for cheletropic reactions.

exists, for each ground state reaction, an excited state process characterized by reversed stereochemical features. However, the extruded small molecule X(YZ)... will frequently possess many occupied lone pair orbitals, and the accompanying possibility of numerous $n\rightarrow\pi^*$ states raises the possibility in any given case that excited state processes with the *same* stereochemical characteristics as the corresponding ground state transformation may be available.

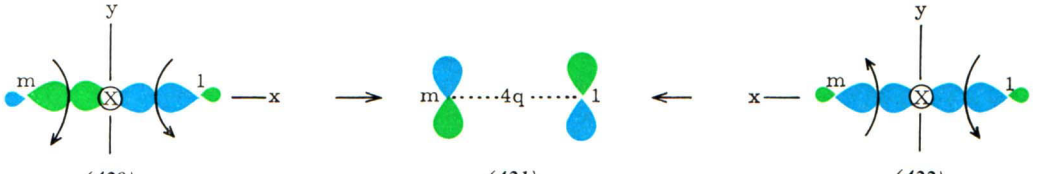
Linear cheletropic fragmentations leading to the production of nitrogen or carbon monoxide represent reactions well-suited for the construction of formal correlation diagrams, which have been drawn by *Lemal* [207], and by *Baldwin* [208], as well as by us. For car-

[207] *D. M. Lemal* and *S. D. McGregor*, J. Amer. chem. Soc. *88*, 1335 (1966).

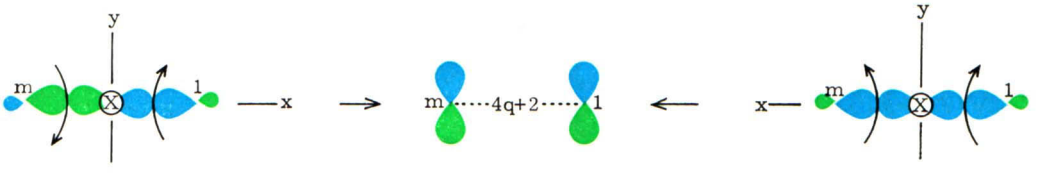
[208] *J. E. Baldwin*, Canad. J. Chem. *44*, 2051 (1966).



(419)

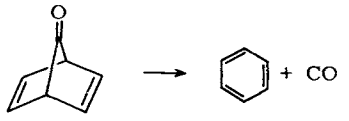


(420) (421) (422)



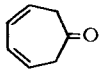
(423) (424) (425)

bon monoxide elimination no direct stereochemical results are available. It is clear, however, that cyclopent-3-en-1-ones ($m=4$) undergo decarbonylation readily, apparently in a concerted manner [208]. In this connection, the failure of attempts to prepare norbornadien-7-one *(426)*, may be contrasted with the stability of norbornanones [209].



(426)

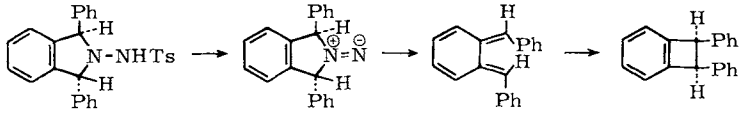
A case with $m=6$ is represented by 3,5-cycloheptadienone *(427)*, which in one of the few known condensed-phase decarbonylations, undergoes photolysis to hexatriene and carbon monoxide [210].



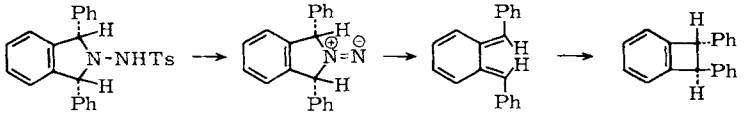
(427)

(428)

The elimination of nitrogen from diazenes *(428)* has been carefully studied by *Lemal* [207]. The process is stereospecific and disrotatory, as predicted; the linear disrotatory path is clearly one involving less strain than the non-linear conrotatory alternative in this case.



(429)



(430)

Remarkable sequences [*(429)*, *(430)*] comprising disrotatory nitrogen eliminations, followed by conrotatory electrocyclic reactions have been revealed by *Carpino* [211].

The reversible, facile addition of sulfur dioxide [212] to dienes is well known [213]. The expected disrotatory course for the elimination of sulfur dioxide from a butadiene sulfone has been established [214]. The corresponding photochemical process is not completely stereospecific, but a clear preference for the conrotatory path is shown [215]. Sulfur dioxide also readily undergoes 1,6-addition to 3-*cis*-hexatrienes; the reverse process has recently been shown to proceed in a conrotatory fashion, and must therefore be classified as a linear cheletropic reaction [216].

Cheletropic reactions in which a three-membered ring is produced or destroyed, *e.g.* fragmentations of type *(411)* in which $m = 2$, are of special interest in that geometric factors require that they take place in a disrotatory, or suprafacial manner. Consequently, these transformations must occur by the non-linear cheletropic path.

The well-known [217] stereospecific combination of singlet carbenes with olefins to give cyclopropanes undoubtedly falls in the non-linear cheletropic class [218].

Cyclopropenones and cyclopropanones lose carbon monoxide thermally under mild conditions [219,220], and even more readily on irradiation [219,221]. Stereochemical information on the decarbonylation is lacking. It has, however, been clearly demonstrated that nitrogen is stereospecifically extruded in a disrotatory fashion from alkyl-substituted three-membered ring

[209] See, for example, *S. Yankelevich* and *B. Fuchs*, Tetrahedron Letters *1967*, 4945.

[210] *O. L. Chapman* and *G. W. Borden*, J. org. Chem. *26*, 4185 (1961); *O. L. Chapman, D. J. Pasto, G. W. Borden*, and *A. A. Griswold*, J. Amer. chem. Soc. *84*, 1220 (1962); *D. I. Schuster, B. R. Sckolnick*, and *F.-T. H. Lee, ibid. 90*, 1300 (1968).

[211] *L. A. Carpino*, Chem. Commun. *1966*, 494.

[212] For molecular orbital descriptions of sulfur dioxide and sulfones, see *W. Moffitt*, Proc. Roy. Soc. *A 200*, 409 (1950).

[213] *H. Staudinger* and *B. Ritzenhaler*, Ber. dtsch. chem. Ges. *68*, 455 (1935); *G. Hesse, E. Reichold*, and *S. Majmudar*, Chem. Ber. *90*, 2106 (1957); *M. P. Cava* and *A. A. Deana*, J. Amer. chem. Soc. *81*, 4266 (1959). The last group has also described some interesting selective photochemical eliminations of sulfur dioxide: *M. P. Cava, R. H. Schlessinger*, and *J. P. Van Meter*, J. Amer. chem. Soc. *86*, 3173 (1964).

[214] *W. L. Mock*, J. Amer. chem. Soc. *88*, 2857 (1966); *S. D. McGregor* and *D. M. Lemal, ibid. 88*, 2858 (1966).

[215] *J. Saltiel* and *L. Metts*, J. Amer. chem. Soc. *89*, 2232 (1967).

[216] *W. L. Mock*, J. Amer. chem. Soc. *89*, 1281 (1967); *W. L. Mock, ibid. 91*, 5682 (1969).

[217] *P. S. Skell* and *R. C. Woodworth*, J. Amer. chem. Soc. *78*, 4496 (1956); *81*, 3383 (1959); *P. S. Skell* and *A. Y. Garner, ibid. 78*, 5430 (1956); *W. von E. Doering* and *P. LaFlamme, ibid. 78*, 5447 (1956); *H. M. Frey, ibid. 80*, 5005 (1958); *W. R. Moore, W. R. Moser*, and *J. E. LaPrade*, J. org. Chem. *28*, 2200 (1963).

[218] For this reaction, semiempirical calculations yield results in striking concordance with the analysis of non-linear cheletropic processes presented here. *Cf. R. Hoffmann*, J. Amer. chem. Soc. *90*, 1475 (1968).

[219] *R. Breslow, T. Eicher, A. Krebs, R. A. Peterson*, and *J. Posner*, J. Amer. chem. Soc. *87*, 1320 (1965); *R. Breslow, L. J. Altman, A. Krebs, E. Mohacsi, I. Murata, R. A. Peterson*, and *J. Posner, ibid. 87*, 1326 (1965); *R. Breslow* and *G. Ryan, ibid. 89*, 3073 (1967).

[220] *N. J. Turro, P. A. Leermakers, H. R. Wilson, D. C. Neckers, G. W. Byers*, and *G. F. Vesley*, J. Amer. chem. Soc. *87*, 2613 (1965).

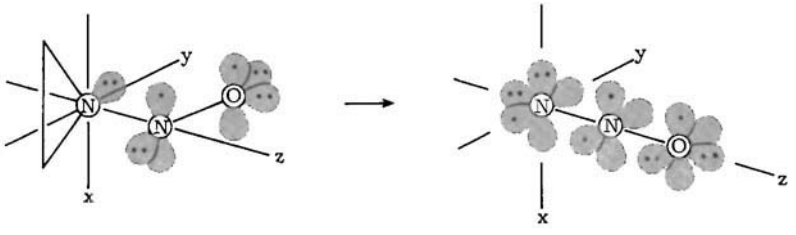
[221] *D. C. Zecher* and *R. West*, J. Amer. chem. Soc. *89*, 153 (1967).

diazenes *(431)* [222]; this change must follow the non-linear path, with x-displacement of N-2 in the plane of the aziridine ring as reaction proceeds.

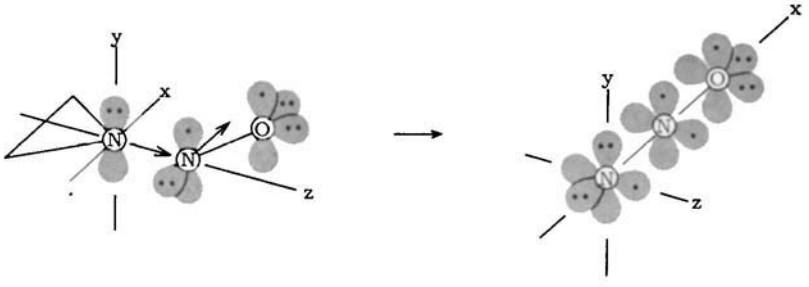
(431)

Sulfur dioxide is readily lost from episulfones in a stereospecific disrotatory manner [223,224]. In order to circumvent the problem which seemed to be posed by the fact that linear cheletropic fragmentation is symmetry-forbidden in this case, it has been suggested [224] that the reaction might proceed in a non-concerted way, through a discrete intermediate. It is now clear that the available evidence is also consistent with the view that the elimination follows the concerted symmetry-allowed non-linear cheletropic path [*cf. (418)*].

The observed ready elimination of nitrous oxide *(433)* from *N*-nitrosoaziridines [225] probably also follows the non-linear cheletropic path [*(432)*→*(433)*]; note that the $4\pi_y$ system remains intact throughout the reaction, and that an x-symmetric lone pair at nitrogen in *(433)* is derived from the bonding antisymmetric σ orbital of the aziridine ring. However, an interesting alternative should be considered. If the nitroso compound be allowed to achieve the conformation *(434)*, the unshared electron pair at the pyramidal aziridine nitrogen atom may become one of the z-symmetric lone pairs of nitrous oxide *(435)*, while the electron pair from the bonding antisymmetric σ orbital of the aziridine ring enters the $4\pi_x$ system. In view of the fact that the uncoupling of two electrons from the $4\pi_y$ system of *(432)* may require *ca.* 23 kcal/mole, as estimated from the barrier to rotation in *N*-nitrosoamines [226], it seems unlikely that the molecule will make use of this alternative symmetry-allowed process to destroy itself.

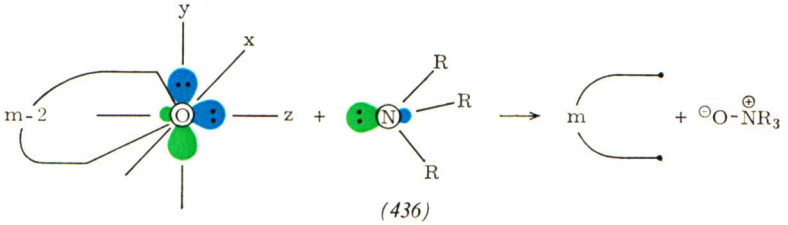


(434) *(435)*



(432) *(433)*

The hypothetical abstraction reaction *(436)* provides a further example of a cheletropic change. If the abstraction takes place in a *linear* fashion, the lone pair of the amine and the two oxygen lone pairs are transformed into the N-O bond and the z and y-axis unshared pairs of the *N*-oxide *(437)*. The remaining x-axis lone pair of the *N*-oxide must be taken from the antisymmetric σ orbital of the breaking carbon-oxygen bonds. Therefore, two electrons from the corresponding symmetric σ orbital must be delivered to the polyene product.



(436)

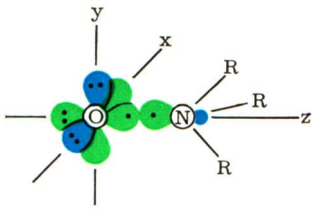
[222] *J. P. Freeman* and *W. H. Graham*, J. Amer. chem. Soc. *89*, 1761 (1967). However, the corresponding aryl-substituted case proceeds in a non-stereospecific manner (personal communication from *L. A. Carpino*).

[223] *N. P. Neureiter* and *F. G. Bordwell*, J. Amer. chem. Soc. *85*, 1210 (1963); *N. Tokura*, *T. Nagai*, and *S. Matsumara*, J. org. Chem. *31*, 349 (1966); *L. A. Carpino* and *L. V. McAdams III*, J. Amer. chem. Soc. *87*, 5804 (1965); *N. P. Neureiter*, *ibid. 88*, 558 (1966); *L. A. Paquette*, Accounts Chem. Res. *1*, 209 (1968).

[224] *F. G. Bordwell*, *J. M. Williams, jr.*, *E. B. Hoyt, jr.*, and *B. B. Jarvis*, J. Amer. chem. Soc. *90*, 429 (1968).

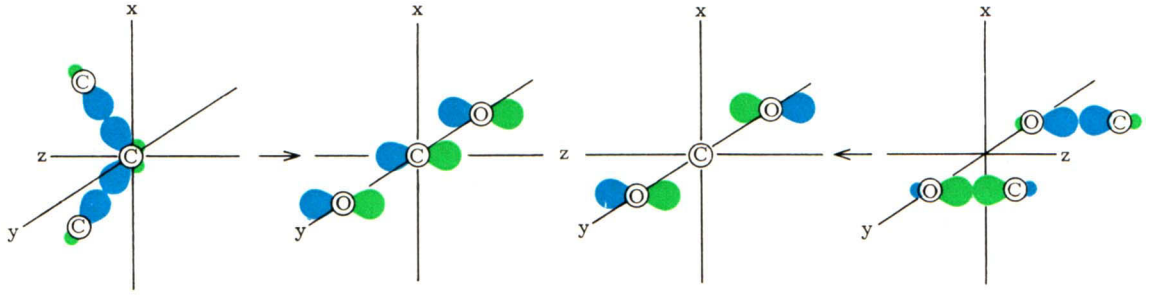
[225] *R. D. Clark* and *G. K. Helmkamp*, J. org. Chem. *29*,1316 (1964).

[226] *C. E. Looney*, *W. D. Phillips*, and *E. L. Reilly*, J. Amer. chem. Soc. *79*, 6136 (1957).



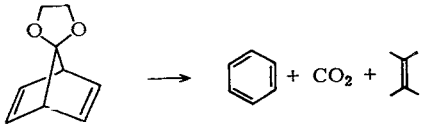
(437)

Consequently, the reaction must occur in a disrotatory sense when $m=4q+2$, or conrotatory when $m=4q$. If, on the other hand, the amine attacks in a *non-linear* manner, *i.e.* in the xz plane, but in the x direction, the stereochemical consequences are precisely reversed. A possible analogue of the linear reaction is available in the stereospecific abstraction of sulfur from the *cis*- and *trans*-butene episulfides by phosphines [227].



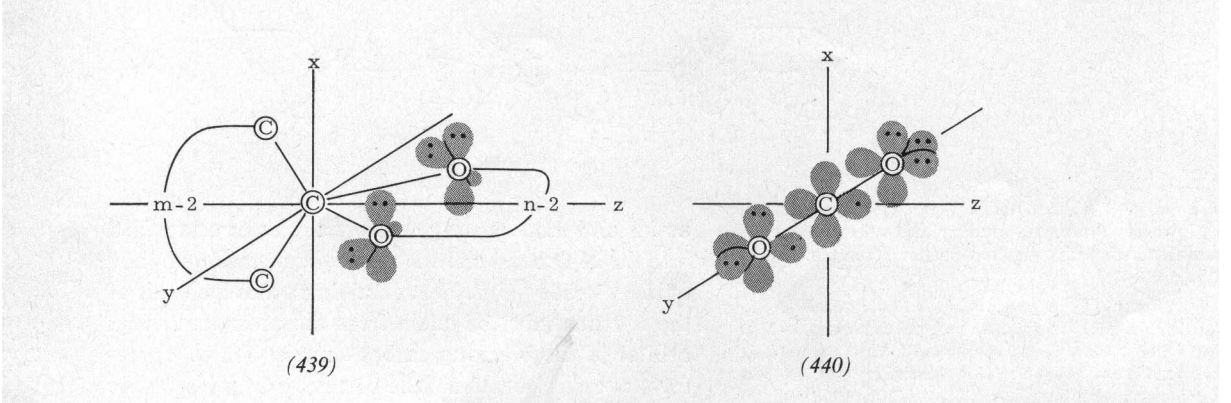
(441) (442) (443) (444)

A fascinating concatenation of a cheletropic fragmentation with a vicinal elimination is presented by the decomposition of a spiroketal to carbon dioxide and two olefins. As yet, the only known instances of the reaction involve ethylene ketals derived from substituted



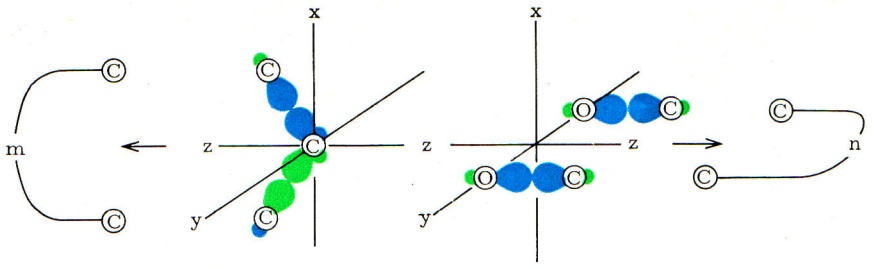
(438)

norbornadienones (438) [228]. It is most interesting to examine the stereochemical aspects of the process in the general case (439); m and n represent the numbers of electrons in the π systems of the product polyenes. In addition to the four electrons which constitute the skeletal σ bonds, carbon dioxide (440) requires twelve electrons: eight of these populate two perpendicular 4π systems, in the xy and yz planes, respectively, while four occupy two y-symmetric lone pair orbitals. If the reaction under discussion follows the linear cheletropic path, it is clear that the eight lone pair electrons at the oxygen atoms of (439) pass smoothly into the y-symmetric lone pair orbitals and the $4\pi_{xy}$ system of carbon dioxide (440), with conservation of orbital symmetry. Further, the orbitals of the orthogonal $4\pi_{yz}$ system can only be filled by transferring two electrons from the symmetric C–C–C σ orbital (441) to the lowest occupied symmetric π_{yz} orbital (442), and two from the antisymmetric O–C–O σ orbital (444) to the highest occupied π_{yz} orbital (443). Therefore, the electrons occupying the antisymmetric C–C–C σ orbital (446) must be delivered to the highest occupied orbital of the polyene (445), while those in the symmetric O–C–O σ orbital (447) take up their new positions in the highest occupied orbital of the polyene (448). Consequently, the geometric displacements associated with the carbon-carbon bond cleavages will be disrotatory when $m=4q$, or conrotatory when $m=4q+2$; by contrast, the carbon-oxygen scissions will be associated with disrotatory displacements when $n=4q+2$, or conrotatory when $n=4q$. If the reaction follows the *non-linear* cheletropic path, the stereochemical consequences attendant upon the carbon-carbon bond cleavages will of course be reversed. Finally, it may be noted that if there is a minimum in the potential surface for the reaction, representing the intermediacy of a singlet carbene species (449), the analysis in terms of orbital symmetry conservation is unchanged.



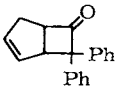
(439) (440)

[227] *D. B. Denney* and *M. J. Boskin*, J. Amer. chem. Soc. *82*, 4736 (1960).
[228] *D. M. Lemal*, *E. P. Gosselink*, and *S. D. McGregor*, J. Amer. chem. Soc. *88*, 528 (1966).

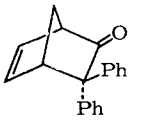


(445) (446) (447) (448)

(449)



(450)



(451)

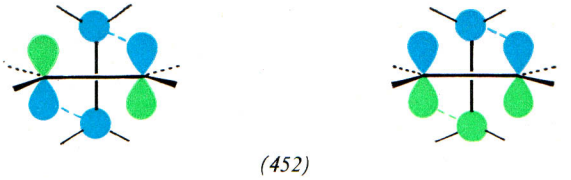
It might appear that in respect to cheletropic reactions, the principle of orbital symmetry conservation is rather generous than discriminate. But that is not so. Cheletropic reactions are unusual in that the stereochemical imperatives imposed by orbital symmetry control upon one of the reactant sites leave no imprint upon the products. Consequently, verification of the predictions which can be made about the detailed course of cheletropic reactions cannot be achieved simply by examining the stereochemistry of the products, and awaits more sophisticated scrutiny.

10.2. Cycloaddition Reactions of Ketenes

The combination of ketenes with olefins to give cyclobutanes has long been known [229]. In recent years, the reaction has been subjected to very searching scrutiny, and the evidence is now conclusive that it is concerted. Thus, the reaction proceeds with a high negative entropy of activation [230], the dependence of rate on solvent polarity is modest [230,231], and stereometric relations in the reactants are maintained in the products [232] – the most striking instance being the formation of distinct adducts from the reactions of dichloroketene with the *cis*- and *trans*-cyclooctenes [233]. Most compelling is the observation that the reaction of ketenes with dienes – even those so constrained as to favor terminal addition – gives only cyclobutanes, and no cyclohexenes [234]. For example, cyclopentadiene and diphenylketene react to give *(450)*; no *(451)* is produced.

A concerted combination of ethylenes to give a cyclobutane must follow the $[\pi 2_s + \pi 2_a]$ path, and in the case at hand the facts demonstrate beyond question that the olefinic reactant participates in a suprafacial way. Is there a special factor in the structure of ketenes which disposes them to play an antarafacial role in cycloaddition reactions?

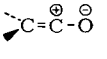
We have seen that the $[\pi 2_s + \pi 2_a]$ process involves orthogonal approach of the reacting species (*cf.* Section 6) – *i.e.* that the π systems must orient themselves as in



(452)

(452) – and we recognize that the path is not normally a readily accessible one, in the absence of special factors (*cf.* Figure 25, Section 6.1). For normal olefins, insurmountable difficulties would appear to be presented by steric hindrance factors, and by transition-state strain associated with framework distortions necessary to maintain effective orbital overlap.

Ketenes are powerful electrophiles. Chemically, the spearhead of their reactivity is the carbon atom of their especially reactive carbonyl group. This dominant aspect of the structure of ketenes, succinctly expressed in the valence-bond structure *(453)*, suggests that we analyze the combination of a vinyl cation *(454)* – *i.e.* a *vinylium* ion – with an olefin from the viewpoint of or-



(453)

(454)

bital symmetry conservation. The relevant orbital diagrams are *(455)* and *(456)*, and the significant differences *vis-a-vis* those for the simple olefin-olefin combination *(452)* are the substantially more favorable situation in respect to steric oppositions, and more especially, the presence of the orthogonal vacant *p* orbital in

[229] *Cf. H. Staudinger:* Die Ketene. Enke, Stuttgart 1912.

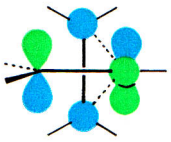
[230] *R. Huisgen, L. A. Feiler,* and *P. Otto,* Tetrahedron Letters *1968*, 4485.

[231] *W. T. Brady* and *H. R. O'Neal,* J. org. Chem. *32*, 612 (1967).

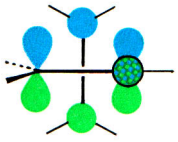
[232] *G. Binsch, L. A. Feiler,* and *R. Huisgen,* Tetrahedron Letters *1968*, 4497; *J. C. Martin, V. W. Goodlett,* and *R. D. Burpitt,* J. org. Chem. *30*, 4309 (1965); *R. Huisgen, L. Feiler,* and *G. Binsch,* Angew. Chem. *76*, 892 (1964); Angew. Chem. internat. Edit. *3*, 753 (1964).

[233] *R. Montaigne* and *L. Ghosez,* Angew. Chem. *80*, 194 (1968); Angew. Chem. internat. Edit. *7*, 221 (1968).

[234] *R. Huisgen* and *P. Otto,* Tetrahedron Letters *1968*, 4491.



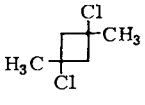
(455)



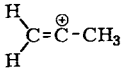
(456)

the vinylium ion [green in *(455)* and checkered in *(456)*]. *It is at once apparent that the latter special feature contributes two strong bonding interactions* [dotted lines in *(455)*] *which are absent from the* $[\pi 2_s+\pi 2_a]$ *reaction path for simple olefins.* It should be noted that the view presented is such that the *top* of the vacant *p* orbital is seen, and that it is the bottom of that orbital which is bonding to the occupied π system of the simple olefinic reactant [*cf. (455)*]. To put the matter in another way, the normal symmetry-allowed combination of a cation with an ethylene, in this unique situation sets the stage for and is coalescent with the $[\pi 2_s+\pi 2_a]$ cycloaddition reaction.

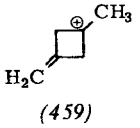
In the light of the analysis just presented, it is clear that a vinylium ion must be regarded as constituted *par excellence* for participation as the $\pi 2_a$ component in the concerted $[\pi 2_s+\pi 2_a]$ cycloaddition. Consequently, it is most gratifying to find that the predicted reaction has in fact been observed, though not hitherto recognized as such. Thus, *Griesbaum* [235] found that allene reacts with hydrogen chloride at −70 °C to give a mixture of the stereoisomeric dichlorodimethylcyclobutanes *(457)*; it is now clear that an initially-produced cation *(458)* combines with a molecule of allene by the



(457)

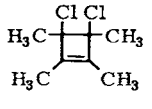


(458)

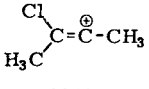


(459)

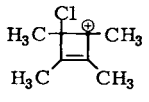
$[\pi 2_s+\pi 2_a]$ route to give *(459)*, which reacts with chloride ion and hydrogen chloride to afford the observed products. Further, the very useful, but surprising – indeed hitherto baffling – synthesis of 1,2-dichloro-1,2,3,4-tetramethylcyclobutene *(460)*, by treatment of 2-butyne with chlorine in the presence of boron trifluoride [236,237], is now readily explicable: $[\pi 2_s+\pi 2_a]$ combination of 2-butyne with the β-chlorovinylium ion *(461)* leads directly to the cyclobutenyl cation *(462)*, whose discharge by chloride ion yields *(460)*. These striking examples leave no doubt that vinylium ions possess in high degree the predicted capacity for concerted combination with $\pi 2_s$ systems.



(460)

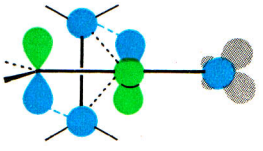


(461)

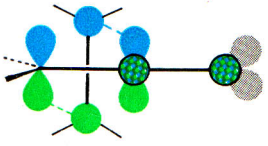


(462)

And now we can answer emphatically in the affirmative the inquiry which launched the discussion just concluded. Ketenes, in their capacity as vinylium ylides *(453)*, are in fact ideally constituted to play an antarafacial role in reaction with $\pi 2_s$ systems, and it is that symmetry-allowed role which they exhibit in the many observed concerted combinations with olefinic systems. Of course, ketenes are not simple vinylium ions, but



(463)



(464)

detailed analysis reveals that the circumstances are not significantly altered in the more complicated case. Thus, for ketenes the relevant orbital diagrams are *(463)* and *(464)*. In this case the place of the vacant *p* orbital of the simple vinylium ion is taken by the unoccupied $\pi^*_{C=O}$ orbital of the ketene molecule [*cf. (463)*]; it is the exceptionally low-lying position of this orbital which accounts in molecular orbital terms for the high electrophilic reactivity of ketenes. As in the simpler case, there is no net change in bonding through interaction of the extra π system with the π^* orbital of the $\pi 2_s$ component [*cf. (456)* and *(464)*]. Finally, it should be pointed out explicitly that interaction of the $\pi_{C=C}$ system of the ketene molecule with the antisymmetric lone pair orbital at the oxygen atom is essentially irrelevant to the matter at hand. This interaction, which is small in terms of energy in any event, creates three new allylic orbitals (Figure 45). Of these, two are occupied; the lower simply takes the place of the usual two-orbital π system [*cf. (464)* and *(456)*] and the electrons in the middle orbital return to their original lone pair status as reaction proceeds.

In the dimerization of ketenes – also regarded as concerted [238] – one of the ketene molecules exercises its unique potentiality as a $\pi 2_a$ component, while the other acts in normal $\pi 2_s$ fashion. In that connection it should be noted that the participation of a ketene as a $\pi 2_s$ component is not facilitated by the presence of the orthogonal $\pi_{C=O}$ system, nor is the interaction with the lone

[235] *K. Griesbaum, W. Naegele,* and *G. G. Wanless,* J. Amer. chem. Soc. *87*, 3151 (1965); *K. Griesbaum,* Angew. Chem. *78*, 953 (1966); Angew. Chem. internat. Edit. *5*, 933 (1966).

[236] *R. Criegee* and *A. Moschel,* Chem. Ber. *92*, 2181 (1959).

[237] *I. V. Smirnov-Zamkov,* Doklady Akad. Nauk SSSR *83*, 869 (1952); *I. V. Smirnov-Zamkov* and *N. A. Kostromina,* Ukr. Khim. Zhur. *21*, 233 (1953).

[238] *R. Huisgen* and *P. Otto,* J. Amer. chem. Soc. *90*, 5342 (1968).

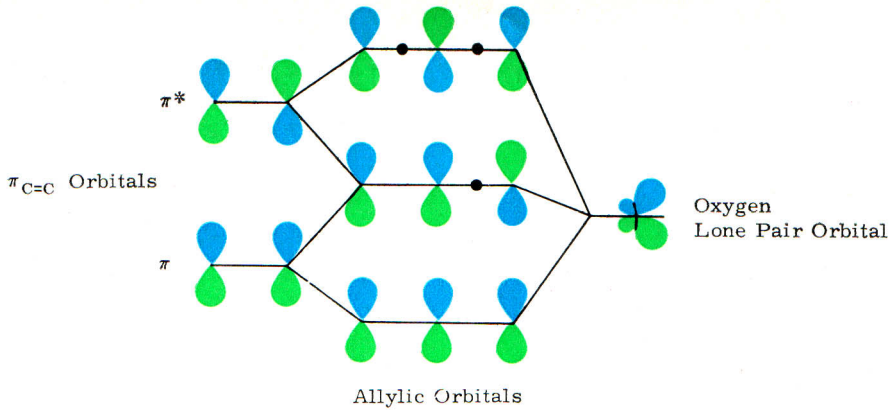


Figure 45. Allylic orbitals in the ketene molecule. — Note that as a consequence of the relative stability of the occupied atomic oxygen orbital, the node in the middle allylic orbital is not at the central atom, as it would be in a three-carbon system, and must be located between carbon and oxygen.

pair at oxygen expected to have a major effect. Thus, in participating in cycloaddition reactions as $\pi 2_s$ components, ketenes should not differ markedly from normal alkyl ethylenes. Consequently, in the reactions of ketenes with dienes, the normal symmetry-allowed $[\pi 4_s+\pi 2_s]$ reaction is not expected to be a ready one. Further, the $[\pi 4_s+\pi 2_a]$ reaction is of course symmetry-forbidden, and the presence of an orthogonal vacant *p* orbital, or low-lying $\pi^*_{C=O}$ system, cannot facilitate the $[\pi 4_a+\pi 2_a]$ process. Taken together, these circumstances account for the formation of cyclobutanones to the exclusion of cyclohexenones when ketenes react with simple dienes.

11. Generalized Selection Rules for Pericyclic Reactions

In our development of the theme of orbital symmetry control of concerted chemical changes, we have laid the basis for a general consideration of all *pericyclic* reactions – that is, reactions in which all first-order changes in bonding relationships take place in concert on a closed curve. Thus, we have discussed in detail the special characteristic features of several clearly differentiable reaction types. But we have also made it clear that the different classes have much in common. In particular, we have pointed out that electrocyclic reactions and sigmatropic changes can as well be treated as concerted intramolecular cycloaddition processes. Now, we develop further the important generalization that all pericyclic reactions may be categorized as concerted cycloaddition processes, and must obey the selection rules for such changes.

The selection rules for two-component cycloadditions [*cf.* Figure 22, Section 6] may easily be generalized by induction to include any number of components. In that way we derive the following general rule for all pericyclic changes:

A ground-state pericyclic change is symmetry-allowed when the total number of $(4q+2)_s$ *and* $(4r)_a$ *components is odd.*

Obviously, if the designated total is *even*, the reaction is symmetry-forbidden. Odd-electron systems generally conform to the pattern for even-numbered systems containing one more electron, and there is in general, corresponding to every ground-state reaction, a related excited-state process for which the rule is simply reversed.

In order to complete the generalized description of pericyclic reactions, it is necessary at this point to introduce one further, and final, convention. Clearly, when q or $r = 0$, a $4r$ component necessarily represents a single atomic orbital, and a $4q+2$ component may do so. That is to say, such a single orbital component may be vacant or occupied. Like any other component, single orbital components may participate in either a suprafacial or an antarafacial manner, and they require a special designation – a presubscript ω – consistent with the characterization of σ and π components, thus:

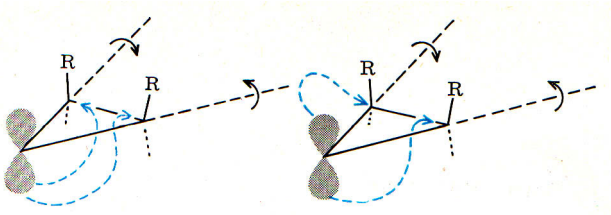
$$\omega 0_s \quad \omega 0_a \quad \omega 2_s \quad \omega 2_a$$

With the tools now at hand, it is a simple matter to classify any pericyclic reaction, and to determine whether it is symmetry-allowed. We shall now recapitulate the examples mentioned earlier, and exemplify the procedure in some new instances. Note that the dashed lines in all of the analyses represent bonding interactions in the transition state.

a) The conrotatory electrocyclic opening of cyclobutenes [*cf.* Figures 23 and 24, Section 6] may be regarded either as a $[\pi 2_s+\sigma 2_a]$ or a $[\pi 2_a+\sigma 2_s]$ process, and the general rule shows at once that it is symmetry-allowed.

b) The suprafacial [1,3] sigmatropic shift with inversion at the migrating center [*cf.* Figure 34, Section 7] may also be regarded as a symmetry-allowed $[\pi 2_s+\sigma 2_a]$ or a $[\pi 2_a+\sigma 2_s]$ change.

c) The disrotatory electrocyclic transformation of a cyclopropyl cation to an allyl cation may be regarded either as an $[\omega 0_s+\sigma 2_s]$ *(465)* or as an $[\omega 0_a+\sigma 2_a]$ *(466)* process, and is symmetry-allowed. Note that in a formal sense, when a single ω component is involved in a pericyclic reaction, the ω orbital moves to a new position, and one of the dashed lines used in the analysis vanishes in the product.



$[\omega 0_s+\sigma 2_s]$ (465) $[\omega 0_a+\sigma 2_a]$ (466)

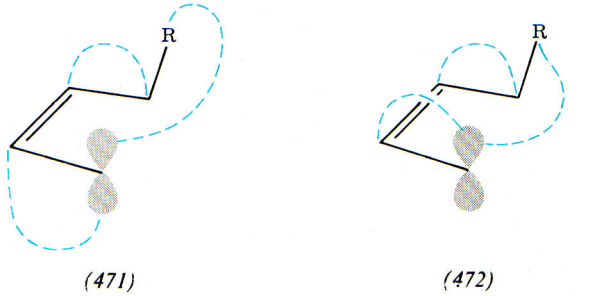
d) The [1,2] sigmatropic shift within a cation cannot take place with inversion of the migrating group, since the $[\omega 0_a+\sigma 2_s]$ *(467)* and $[\omega 0_s+\sigma 2_a]$ *(468)* processes are symmetry-forbidden. Note that antarafacial bonding

$[\omega 0_a+\sigma 2_s]$ (467) $[\omega 0_s+\sigma 2_a]$ (468)

interaction between two atoms joined by a non-participating bond and bridged by a single atom is physically impossible. Thus, the $[\omega 0_s+\sigma 2_s]$ processes depicted in *(469)* and *(470)* both represent the symmetry-allowed but physically unrealizable antarafacial [1,2] sigmatropic shift with inversion at the migrating center.

(469) (470)

e) The suprafacial [1,4] sigmatropic shift with inversion at the migrating center may be regarded, *i.a.*, as a symmetry-allowed $[\pi 2_a+\omega 0_a+\sigma 2_a]$ process *(471)*. All of the



(471) (472)

alternative formal classifications *(473)*, each of which represents a symmetry-allowed reaction, require inversion at R, and no allowed suprafacial process exists in which R migrates with retention; for example, the

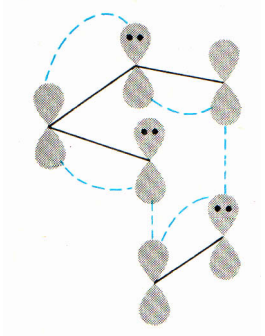
$[\pi 2_s+\omega 0_a+\sigma 2_s]$
$[\pi 2_s+\omega 0_s+\sigma 2_a]$ *(473)*
$[\pi 2_a+\omega 0_s+\sigma 2_s]$

$[\pi 2_s+\omega 0_s+\sigma 2_s]$ pericyclic reaction depicted in *(472)* is obviously symmetry-forbidden.

f) The non-linear cheletropic extrusion of sulfur dioxide from an episulfone [*cf.* *(418)*, Section 10.1] is a symmetry-allowed $[\sigma 2_s+\sigma 2_a]$ reaction *(474)*, and the reverse process would be a $[\pi 2_s+\omega 2_a]$ change *(475)*.

(474) (475)

g) The Diels-Alder reaction is obviously a symmetry-allowed $[\pi 4_s+\pi 2_s]$ change, but it could be analyzed as an allowed $[\omega 0_s+\omega 2_s+\omega 0_a+\omega 2_a+\omega 0_s+\omega 2_s]$ process *(476)*.



(476)

The example is included partly in a sportive spirit, but it does have the serious purposes of indicating that (i) the participation of any number and kind of ω components in a pericyclic reaction presents no occasion for difficulty in analyzing the process in terms of the general rule, and (ii) polarization of the bonds involved in a pericyclic reaction in no way alters the orbital symmetry control to which it is subject.

It should be emphasized that use of the general selection rule for pericyclic reactions must always be subject to the following precautions.

a) The geometry of each individual case must be examined on its merits in order to ascertain whether the process is physically realizable. We have already exemplified, in d) above, and in our discussion of the rearrangement of the ester of Feist's acid [*cf.* *(331)*, Section 7.1], situations in which formally symmetry-allowed processes are geometrically impossible.

b) In cases in which the reacting components are directly joined by non-participating bonds, forced ancillary off-circuit antibonding interactions may render an otherwise allowed reaction symmetry-forbidden. Thus, prismane cannot be converted to three isolated, non-interacting, ground state ethylene moieties by a $[\sigma 2_s+\sigma 2_a+\sigma 2_a]$ process. The geometric constraints imposed by the non-participant σ framework require that the ethylene moieties produced in such a reaction inter-

act strongly in an antibonding way, and the orbital symmetry-imposed electronic configuration of the array is in fact that of a doubly excited state of the actual product benzene [*cf.* Section 6.4]. Any case in which similar circumstances may be suspected should be subjected individually to complete analysis in the light of the principle of orbital symmetry conservation.

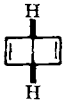
12. Violations

There are none!

Nor can violations be expected of so fundamental a principle of maximum bonding. All the more is it then important to give consideration to some reactions which might appear on casual inspection to contravene orbital symmetry conservation.

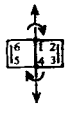
First, it should be emphasized explicitly here that a given symmetry-allowed concerted reaction need not necessarily represent the manner in which reacting molecules will actually comport themselves. Quite possibly another path, involving reactive *intermediates* of relatively low energy may be followed. The other side of this coin is that molecules may in some cases combine, or decompose, to give the very products which would result from symmetry-forbidden concerted processes. In these cases it is clear that the actual reaction path is a non-concerted one, involving discrete intermediates; indeed, the principle of orbital symmetry conservation is very useful in defining conditions in which such processes may be expected. Such are often the circumstances in the combination of ethylenes to give cyclobutanes. The direct, concerted $[\pi 2_s + \pi 2_s]$ combination is of course symmetry-forbidden, and the allowed $[\pi 2_s + \pi 2_a]$ reaction is realizable only in special circumstances. Nevertheless, there are a substantial number of instances, lacking the special prerequisites for the $[\pi 2_s + \pi 2_a]$ reaction, in which the combination of two ethylenic molecules leads to a cyclobutane [239]. And in such cases, the available evidence is compelling in favor of the view that discrete diradical or ionic intermediates are involved [240]; further, it is of obvious significance that such reactions are observed only when the reactant olefins are ornamented by substituents so constituted as to provide effective stabilization of the requisite intermediate.

It remains only to address a few final comments to the matter of symmetry-forbidden reactions which may occur in a concerted fashion. In principle, of course, given sufficient energy, and means of constraining molecules in energy-rich configurations, we could bring about any symmetry-forbidden reaction. A very powerful Maxwell demon could make a molecule of cyclobutane by grasping a molecule of ethylene in each hand, and – not without an impressive exhibition of his strength – forcing the two together face-to-face. He could seize a molecule of cyclobutene at its methylene groups, and tear it open in a disrotatory fashion to obtain butadiene. But without such demoniac intervention, molecules will very rarely comport themselves in like fashion – since reaction paths with lower energy surfaces than those associated with symmetry-forbidden processes will almost always be available. None the less, the possibility remains that molecules may be constructed within which no other such alternatives exist; then, provided that the molecule be sufficiently energized, the symmetry-forbidden path would necessarily be followed. Derivatives of *cis*-bicyclo[2.2.0]hexadiene *(477)* quite possibly exemplify such a process. These substances do undergo conversion to the corresponding

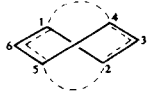


(477)

benzenoid isomers, with an activation energy in the neighborhood of 37 kcal/mole [241]. The simple disrotatory cleavage of the central bond is symmetry-forbidden, but *(477)* is already strained to the extent of *ca.* sixty kilocalories relative to benzene [242], and the addition of a further thirty-seven kilocalories may sufficiently energize the molecule as to overcome the prohibition against disrotatory cleavage. But even in this case, the possibility is not entirely excluded that events may take another course, and that the transformation may proceed through a discrete intermediate. For example, if the breaking of the central bond of *(477)* is accompanied by a quasi-conrotatory skewing distortion [*cf. (478)*] – a boat→twist-boat transformation – the result *(479)* is an array containing two skewed allyl radical systems [C(5)-C(6)-C(1) and C(2)-C(3)-C(4)], joined orthogonally at their termini. Were all bonding between C-1 and C-4 to be lost concurrently with these



(478)



(479)

motions, the related symmetry-derived antibonding components in the transition state for conversion to benzene would vanish, and the process could continue

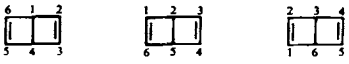
[239] An excellent review is available: *J. D. Roberts* and *C. M. Sharts*, Organic Reactions *12*, 1 (1962).

[240] *P. D. Bartlett, L. K. Montgomery*, and *B. Seidel*, J. Amer. chem. Soc. *86*, 616 (1964); *L. K. Montgomery, K. Schueller*, and *P. D. Bartlett, ibid. 86*, 622 (1964); *P. D. Bartlett* and *L. K. Montgomery, ibid. 86*, 628 (1964); *P. D. Bartlett*, Science *159*, 833 (1968).

[241] *J. F. M. Oth*, Angew. Chem. *80*, 633 (1968); Angew. Chem. internat. Edit. *7*, 646 (1968); Rec. Trav. Chim. Pays-Bas, *87*, 1185 (1968); *H. C. Volger* and *H. Hogeveen*, Rec. Trav. Chim. Pays-Bas *86*, 830 (1967).

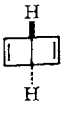
[242] *W. Schäfer*, Angew. Chem. *78*, 716 (1966); Angew. Chem. internat. Edit. *5*, 669 (1966).

to completion by appropriate symmetry-allowed combinations of the isolated allyl radicals. Even if some 1,4 bonding is retained – and of course, were that the case, some 2,5 bonding would be generated – the corresponding symmetry-derived antibonding components in the transition state *(479)* will be smaller than those in the transition state for the simple symmetry-forbidden disrotatory cleavage; it is of special interest that if *(479)* should represent the transition state for the conversion of bicyclohexadienes to aromatic compounds, the former should be susceptible of isomerization in the sense *(480)→(481)→(482)*.



(480) *(481)* *(482)*

Finally, we emphasize the fact that *cis*-bicyclo-[2.2.0]hexadienes owe their remarkable durability to symmetry-imposed barriers, and, to introduce a light note, suggest that our fellow chemists estimate how long the isomer *(483)* – put together, perhaps, by our versatile demon – would survive.



(483)

13. Other Theoretical Work

In view of the fact that the principle of conservation of orbital symmetry has been found to be an exceptionally powerful predictive and interpretive tool, it is not surprising that a number of alternative theoretical approaches have been set forth. In all cases the central conclusions, of necessity, agree in all respects with our own. Reference should be made to the interesting contributions of *Fukui* [243], *Salem* [244], *Zimmerman* [245], *Dewar* [246], *Oosterhoff* and *van der Lugt* [247], and, of course, *Longuet-Higgins* and *Abrahamson* [248].

It is also appropriate here to mention some earlier studies relevant to and antecedent to our own. Correlation diagrams for the simplest chemical reactions are no novelty; some interesting applications are presented by *Laidler* [249]. Such diagrams were extensively used by *Griffing* [250], but were incorrectly interpreted. In an important paper by *Herzfeld* [251] it was shown that for a set of $2p$ orbitals the number of nodes in a molecular system is conserved as atoms are brought near each other, and that when the orbitals are alike no two states of different energy can have the same number of nodes. *Bader* [252] presented a novel and interesting discussion of some elementary reactions.

We have already mentioned the suggestion of *Oosterhoff* [253] that orbital symmetry might play a role in electrocyclic reactions. The advantages of a six-electron transition state were pointed out by *Syrkin* [254]. His papers, and those by *Balaban* [255] and *Mathieu* and *Valls* [256] are a rich source of references for possible concerted reactions.

Numerous reviews summarizing various aspects of the application of the principle of conservation of orbital symmetry have already appeared [257].

The frontier-electron theory was developed by *Fukui*, who has continued an intensive exploration of various methods of calculation pertinent to problems of chemical reactivity [258]. In some of our work we have utilized extended Hückel calculations [259] to confirm qualitative conclusions. The virtue of these approximate calculations lies in the fact that they may be applied to σ as well as π systems. The method was originally developed in collaboration with *Lipscomb* and owes much to previous work of *Longuet-Higgins* on boron hydrides.

---

[243] *K. Fukui*, Tetrahedron Letters *1965*, 2009, 2427; Bull. chem. Soc. Japan *39*, 498 (1966); *K. Fukui* and *H. Fujimoto*, Tetrahedron Letters *1966*, 251; Bull. chem. Soc. Japan *39*, 2116 (1966); *40*, 2018 (1967).

[244] *L. Salem*, J. Amer. chem. Soc. *90*, 543, 553 (1968).

[245] *H. E. Zimmerman*, J. Amer. chem. Soc. *88*, 1563, 1566 (1966).

[246] *M. J. S. Dewar*, Tetrahedron, Suppl. 8, p. 75 (1966); Aromaticity. Special Publication of The Chemical Society No. 21, London 1967, p. 177.

[247] *W. Th. A. M. van der Lugt* and *L. J. Oosterhoff*, Chem. Commun. *1968*, 1235.

[248] *H. C. Longuet-Higgins* and *E. W. Abrahamson*, J. Amer. chem. Soc. *87*, 2045 (1965).

[249] *K. J. Laidler:* The Chemical Kinetics of Excited States. Oxford University Press, Oxford 1955.

[250] *V. Griffing*, J. chem. Physics *25*, 1015 (1955); J. phys. Chem. *61*, 11 (1957).

[251] *K. F. Herzfeld*, Z. Naturforschg. *3a*, 457 (1948); Rev. mod. Physics *41*, 527 (1949).

[252] *R. F. W. Bader*, Canad. J. Chem. *40*, 1164 (1962). *Cf.* also *R. G. Pearson*, J. Amer. chem. Soc. *91*, 1252 (1969), and *L. Salem*, Chem. Phys. Letters *3*, 99 (1969).

[253] *L. J. Oosterhoff*, quoted in *E. Havinga* and *J. L. M. A. Schlatmann*, Tetrahedron *16*, 151 (1961).

[254] *Ya. K. Syrkin*, Izv. Akad. Nauk SSSR *1959*, 238, 389, 401, 600.

[255] *A. T. Balaban*, Rev. Roum. Chimie *11*, 1097 (1966); *12*, 875 (1967).

[256] *J. Mathieu* and *J. Valls*, Bull. Soc. chim. France *1957*, 1509.

[257] *Inter alia*, *J. J. Vollmer* and *K. L. Servis*, J. Chem. Educat. *45*, 214 (1968); *S. I. Miller* in *V. Gold:* Advances in Physical Organic Chemistry. Academic Press, New York 1968, Vol. 6, p. 185; *G. B. Gill*, Quart. Rev. *22*, 338 (1968); *D. Seebach*, Fortschr. chem. Forsch. *11*, 177 (1969); *P. Millie*, Bull. Soc. chim. France *1966*, 4031; *M. Orchin* and *H. H. Jaffé:* The Importance of Antibonding Orbitals. Houghton-Mifflin, Boston 1967; *E. M. Kosower:* An Introduction to Physical Organic Chemistry. Wiley, New York 1968; *O. Červinka* and *O. Kříž*, Chem. Listy *61*, 1036 (1967); *62*, 321 (1968); *J. P. M. Houbiers*, Chem. Weekblad *62*, 61 (1966); *C. Hörig*, Z. Chem. *7*, 298 (1967); *M. J. S. Dewar*: The Molecular Orbital Theory of Organic Chemistry. McGraw-Hill, New York 1969.

[258] *K. Fukui* in *P.-O. Löwdin* and *B. Pullman:* Molecular Orbitals in Chemistry, Physics and Biology. Academic Press, New York 1964, p. 513; *K. Fukui* in *O. Sinanoğlu:* Modern Quantum Chemistry. Academic Press, New York 1965, p. 49.

[259] *R. Hoffmann* and *W. N. Lipscomb*, J. chem. Physics *36*, 2179 (1962); *37*, 2872 (1962); *R. Hoffmann*, *ibid. 39*, 1397 (1963); *40*, 2474, 2480, 2745 (1964); Tetrahedron *22*, 521, 539 (1966).

Of special interest are several recent applications of orbital symmetry conservation in novel directions. The derivation of selection rules for the isomerization and substitution reactions of transition metal complexes [260], the suggestion that orbital symmetry is determinative in chemiluminescent reactions [261], and the analysis of the role of orbital symmetry in excited state energy transfer [262] merit particular attention.

14. Conclusion

We have now explicated the principle of conservation of orbital symmetry, and exemplified its use. It may perhaps be appropriate here to emphasize that the central content of the principle lies in the incontrovertible proposition that a chemical reaction will proceed the more readily, the more *bonding* may be maintained throughout the transformation. Consequently, we cannot doubt that the principle will endure, whatever the language in which it may be couched, or whatever greater precision may be developed in its application and extension.

Nor can it be doubted that extension will be made – both of a fundamental and of a detailed nature. Since every elementary step in *any* chemical reaction is a concerted process, correlative ideas must be applicable to *all* reactions. The exploration of applications in inorganic chemistry has barely been begun. And within the realm already delineated, only the imagination sets limits upon the number and variety of new and fascinating molecules which may be designed to favor reactions as yet undiscovered, but now known to be feasible.

Received: January 7, 1969 [A 710 IE]
German version: Angew. Chem. *81*, 797 (1969)

[260] *D. R. Eaton*, J. Amer. chem. Soc. *90*, 4272 (1968).
[261] *F. McCapra*, Chem. Commun. *1968*, 155.
[262] *E. F. Ullman*, J. Amer. chem. Soc. *90*, 4158 (1968).

Classification of Partition Reactions of Inorganic Cations

By H. Specker and A. Kettrup [*]

In partition reactions of inorganic cations, it is necessary to establish the composition of the extracted compounds. The methods used and the limits of their application are described and illustrated for the extraction of cobalt thiocyanates. The results obtained allow new analytical applications, e.g. the fractional extraction of Hg, Bi, Cd, In, and Zn.

1. Introduction

The aim of the present article is to describe the methods that provide information about the composition of an extracted species, as well as their application limits, using the extraction of cobalt thiocyanates as an example.

A general picture will also be given of the extraction of inorganic compounds with ketones and triesters of phosphoric acid as solvents. Extractions with diesters of phosphoric acid and with amines will not be discussed, since these systems were reviewed comparatively recently [1–3].

2. Methods of Determining the Compositions of Extracted Compounds

All the methods described below were originally developed for determination of the compositions of complexes in single-phase, particularly aqueous systems. The question of primary interest is that of the number n of ligands (*e.g.* halide ions) bound per central atom. In extractions with solvents that are capable of coordination, we also wish to know the number r of solvent molecules bound. If a definite compound, *e.g.* a halogenometalate

$$(A^+)_z[ML_n]^{z-} \cdot rS$$

is extracted over a wide concentration range, two series of measurements with suitable variations are generally sufficient to give the numbers of halide and solvent ligands.

The photometrically determined extinction value is very often used as a measure of the concentration of the complex formed in normal solution equilibria;

[*] Prof. Dr. H. Specker and Dr. A. Kettrup
Lehrstuhl für Anorganische Chemie I der Universität
463 Bochum, Gebäude NC (Germany)

[1] *D. F. Peppard* in: Advances in Inorganic Nuclear Chemistry Academic Press, New York 1966, Vol. 9.

[2] *D. Dyrssen, J.-O. Liljenzin*, and *J. Rydberg*: Solvent Extraction Chemistry. North-Holland Publ. Co., Amsterdam 1967.

[3] *A. Kettrup* and *H. Specker*, Fortschr. chem. Forsch. *10*, 237 (1968).