Forschung, Wissenschaft

The Bicycle Rearrangement; A Review of an Unusual Photochemical Reaction *

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Abstract

The bicycle rearrangement is an intriguing reaction in which a divalent carbon, bearing two substituents and bound to a π-system with two sp^5 orbitals, moves along the molecule as if the two sp^5 orbitals were bicycle wheels and the two groups were "handlebars." The rearrangement may be envisaged as involving conversion of one cyclopropyldicarbinyl moiety into another such system.

The rearrangement occurs in a variety of molecular environments. For example, the mechanism of the well-known 2,5-cyclohexadienone rearrangement involves a bicycle step. Also the Di-π-Methane rearrangement has a bicycle step in its mechanism. Additionally, a variety of vinylcyclopropanes with appropriate substitution undergo bicycle rearrangements. These reactions are stereospecific with the groups on the migrating carbon (i.e. the "handlebars") maintaining their stereochemical integrity.

Introduction

It is difficult to delineate the precise beginning of the bicycle rearrangement, since a number of closely related reactions subsequently were recognized as having common mechanistic features. Nevertheless, the story does seem to begin about 1970 when it was reported [1, 2] that the photolysis of 2-methylene-6,6-dimethylbicyclo-[3.1.0]-3-hexene (1) led to the isomeric 2,2-dimethylspiro[2.4]-4,6-heptadiene (2). In parallel, irradiation of the stereoisomeric 2-methylene-5,6-diphenylbicyclo[3.1.0]-3-hexenes (3a, b) led to 1,5-diphenylspiro[2.4]-4,6-heptadiene stereoisomers (4). These rearrangements are depicted in equations 1 and 2.

It was found that the rearrangement proceeded only on direct irradiation, that is, without addition of a sensitizer designed to lead to the triplet. Thus the rearrangement was that of the excited singlet.

Furthermore, the reaction was found to be reasonably stereospecific. Thus the cis stereoisomer of the bicyclic reactant **3a** afforded the syn stereoisomer of spiro product **4a** while the trans-bicyclic reactant **3b** led predominately to the anti spiro product **4b**. Note equations 2a and 2b.

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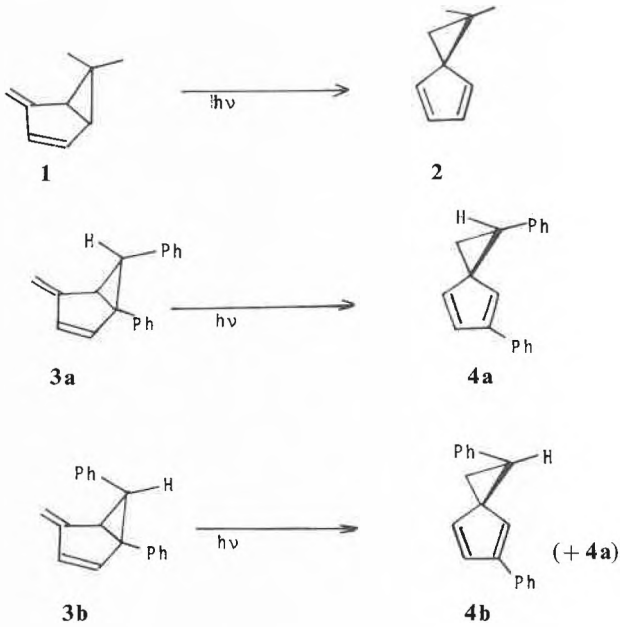
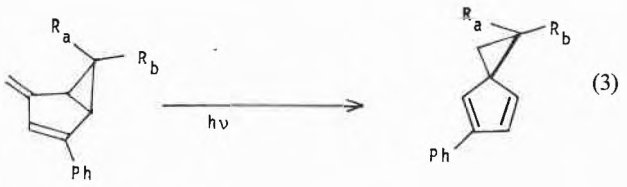


In these early studies the rearrangement was termed a "slither process" in order to convey the idea of the bicycling carbon as moving along the π-system without turning and without losing stereochemical identity. However, with esthetics in mind we have more recently applied the "bicycle rearrangement" description. Thus the rearrangement involves the motion of a single carbon atom bearing two sp^5 orbitals and two substituents. The two sp^5 orbitals may be envisaged as bicycle wheels and the two substituents as "handlebars." The bicycle traverses the π-system as if it were traveling along a narrow pathway.

Before proceeding to a discussion of the reaction mechanism, topology and stereochemistry, we need to consider one further example. Thus, in related studies [3, 4] the photochemistry of 2-methylene-4,6-diphenylbicyclo[3.1.0]-3-hexene (**5**) was investigated. Again the rearrangement was largely stereospecific as outlined in equation 3. We note that the photoproducts are the same

two (i.e. **4a,b**) as obtained starting with the 2-methylene-5,6-diphenylbicyclo[3.1.0]-3-hexene (**3a,b**) reactants.
Interestingly, while the cis-stereoisomers reacted essentially completely stereospecifically, the trans stereoisomers reacted with less than total stereospecificity.



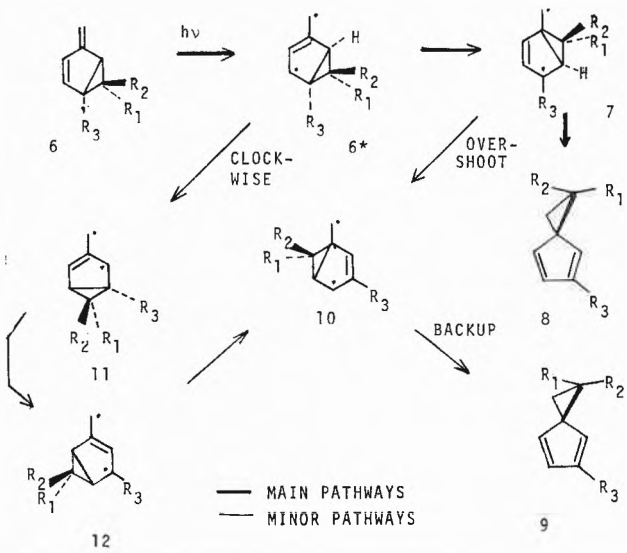
(3)

5a R_a = Ph, R_b = H
5b R_a = H, R_b = Ph

4a R_a = Ph, R_b = H
4b R_a = H, R_b = Ph

The reaction stereospecificity excludes a reaction mechanism in which the divalent carbon is actually expelled as a carbene, thus leaving a fulvene moiety, followed by readdition of the carbene species to the fulvene exocyclic double bond. Such a reaction would not be stereospecific, since the carbene and fulvene pair would lose memory of the reactant's configuration.
The mechanism, written in organic resonance structure terms, shown in Scheme I accounts for the experimental findings. This Scheme includes both the predominant stereochemical course indicated with heavy arrows, and minor processes.
In the major pathway in Scheme I, it is seen that the exo substituent (i.e. R_1) remains exo and the endo substituent (i.e. R_2) remains endo. In the last step in which the bicycling carbon moves onto the exocyclic bond, R_1 becomes syn to R_3 while R_2 becomes anti.
In Scheme I we note that there are two minor pathways and that each, in principle, can account for the reverse stereochemistry. One of these involves the bicycling

Scheme I: Mechanism of the Bicycle Rearrangement.



carbon "overshooting" the side-chain to afford diradical **10** an then "backing up" to afford the minor stereoisomeric product **9**. The other pathway leading to the minor product involves bicycling in a clockwise fashion around the ring via diradical **11**.
In considering possible mechanisms we can recognize that there are two basic modes of migration of a divalent carbon atom from atoms *a* and *b* to atoms *b* and *c*.

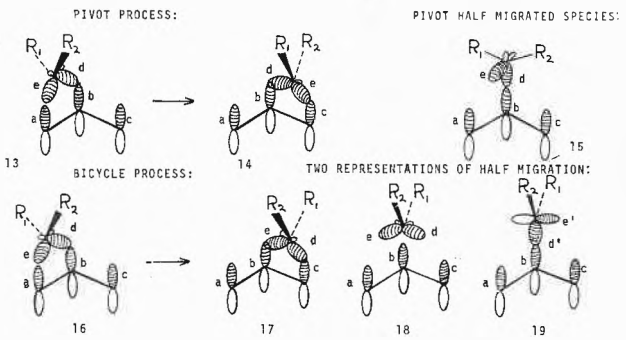


Fig. 1: Bicycle and Pivot Stereochemistries.

The two stereochemistries are shown in Figure 1 and labeled as "bicycle" and "pivot" processes. The bicycle process maintains the endo and exo geometries of the two substituents. Conversely, the pivot process interconverts the endo and exo groups as each step takes place.
It is helpful to inspect the half-rearranged species both for the pivot and for the bicycle processes. Thus at half migration, the pivot species has retained a sigma bond due to overlap between orbitals *b* and *d*. Also there is overlap between the second orbital *e* on the bicycling carbon and orbitals *a* and *c*. Thus bonding *a–e* is being diminished while bonding *c–e* is increasing.
For the half-reacted bicycle species it is seen that there are two quantum mechanically equivalent representations (i.e. **18** and **19**). The first of these is most clearly seen to be related to the starting and final species; the bicycling carbon has two sp^5 orbitals which are the "bicycle wheels". The second representation is uses a different linear combination of two orbitals on the bicycling carbon. This consists of a p-orbital and also an sp^2 hybrid. The sp^2 hybrid is used to maintain σ bonding with orbital *b*. This representation might be termed an "inversion process", since the configuration at the bicycling carbon is, indeed, being inverted with both lobes of the p-orbital being used. That inversion of configuration is equivalent to retention of exo-endo relationships is just a matter of semantics. That the two seemingly different representations are equivalent derives from the equivalency of a p + sp^2 orbital pair to a pair of sp^5 orbitals [5].

We note that an even number of pivot steps will lead to the same stereochemistry as a mechanism using only bicycle steps. In contrast, with an odd number of steps, the two kinds of migrations lead to products with dif-

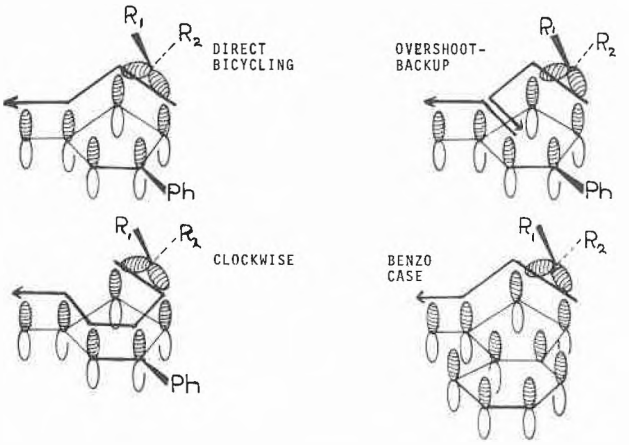


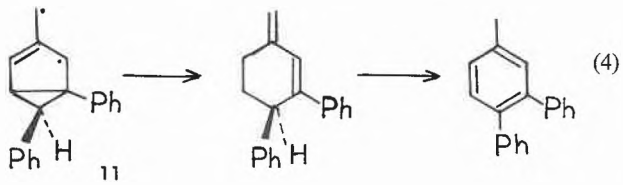
Fig. 2: Topology of Bicycling in the Rearrangement of 5,6-Diphenylbicyclo[3.1.0]hex-2-en-1-one.

ferent stereochemistry. This point will be discussed subsequently.

The possible topologies for the rearrangement in Scheme I are outlined in Figure 2 which includes only the bicycle stereochemistry. The main reaction mechanism makes use of the topology labeled "Direct Bicycling". Included in Fig. 2 are the "Overshoot-backup" and the "Clockwise" topologies. Also included is an example of a benzobicyclic rearrangement to be discussed below.

There is another point of interest. Thus, as minor by-products of these rearrangements a number of diphenyltoluene isomers were isolated. Each of these could be seen to derive from one of the diradical species in Scheme I by fission of an internal three-ring bond. Thus, Species **7**, **10** and **11** in Scheme I are cyclopropyldicarbinyl diradicals of the kind postulated as utilized in the Di-π-Methane rearrangement [6, 7, 8]. Additionally we note that these are 1,4-diradicals which may undergo 2,3-fragmentation to afford 1,4-dienes in a reverse Di-π-Methane rearrangement [9, 10].

That cyclopropyldicarbinyl diradicals may undergo both the bicycling process and the fragmentation process has been established by their independent generation and observation of their behavior [11]. In the present instance diradical **7** should fragment to afford (after tautomerization) 2,4-diphenyltoluene, **10** should give 2,5-diphenyltoluene and **11** should lead to 3,4-diphenyltoluene (note equation 4 for example). In fact, these products were isolated as minor by-products of the irradiations of reactants **3** and **5**.

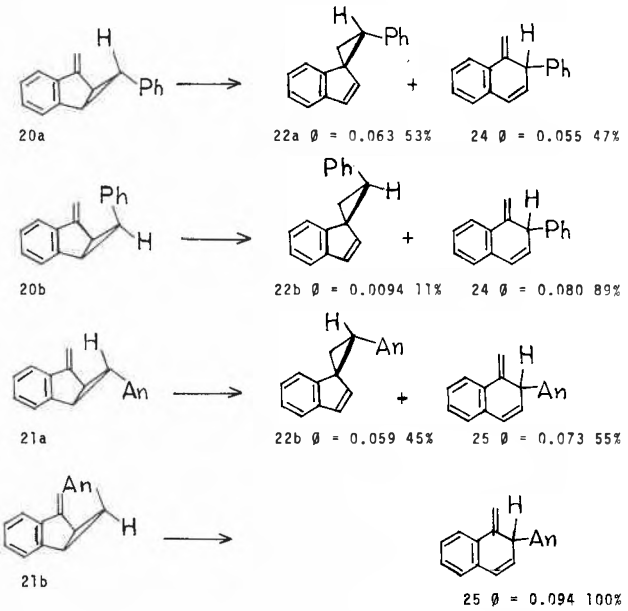


(4)

The formation of these diphenyltoluene by-products may be likened to the dropping of breadcrumbs by Hansel and Gretel leaving a trail identifying their pathway; similarly here the diphenyltoluenes are residues revealing the path taken by the reacting molecule.

A number of interesting aspects remain requiring complete discussion. One is the assumption made in the early studies of the bicycle rearrangement that the loss of stereospecificity [12], arose from the overshoot plus backup or clockwise bicycling mechanisms. A test which was tried [3, 4] made use of a benzo ring fused to the bicyclic system as in **20**. It was presumed that the bicycling carbon would be reluctant to bicycle over the aromatic ring either by the clockwise or by the overshoot plus backup mechanism. The rearrangements of two benzobicyclic reactants are outlined in Scheme II [3, 4].

Scheme II: Bicycle Rearrangements of Two Benzo Bicyclics.



The striking result observed was the total stereo-specificity within experimental limits. Thus with the clockwise bicycle and overshoot-backup mechanisms precluded, pathways affording a second product stereoisomer are unavailable. This, then, confirms the mechanistic source postulated for loss of stereochemistry.

There remains still one other aspect of the basic reaction mechanism. Thus we still have not justified our choice of the bicycle geometry compared with the pivot process for rearrangement. This conclusion derives from the observation that it is the endo isomers which undergo the most competitive 2,3-fragmentation of the diradical species along the reaction route. This is particularly clear in Scheme II where the endo benzobicyclics are seen to afford the dihydronaphthalenes **24** and **25**. These relatively unstable tautomers could be isolated but were readily converted to the corresponding 2-aryl-1-methylnaphthalenes on heating or treatment with acid catalysts. More importantly, these unstable tautomers are the direct products of 1,4-diradical fission after one migra-

tion step. Strikingly, in the case of endo benzobicyclic stereoisomer **21 b** only 2,3-fission product is obtained. In the case of **20 b** the 1,4-diradical fission is the major product.

The tendency for the endo stereoisomers to lead to 2,3-fragmentation is explicable in terms of greater relief of steric strain as the sterically encumbered endo diradical stereoisomers flatten out in the process of three-ring opening. This is depicted in Figure 3.

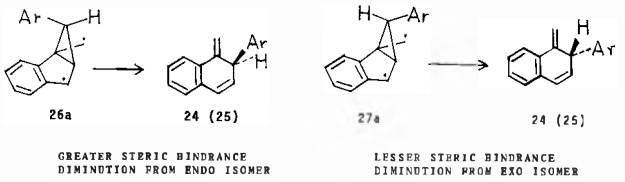
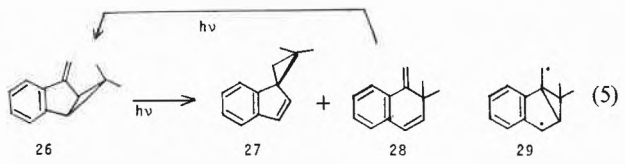


Fig. 3: Comparison of Steric Hindrance Relief in Opening of Endo and Exo Diradicals.

This then leads us to the point that the endo diradicals are formed from endo reactants and exo diradicals are formed from exo reactants only if bicycling rather than pivoting is utilized. This arises since the diradicals are formed in an odd number of steps. If pivoting, instead, were the mechanism utilized, then the endo bicyclic reactants (e. g. **20 b** and **21 b**) would lead to exo diradicals **27a** while the exo bicyclic reactants (e. g. **20 a** and **21 a**) would afford endo diradicals **27 b**. This would result in to the exo reactants giving more 2,3-fragmentation rather than less as observed.

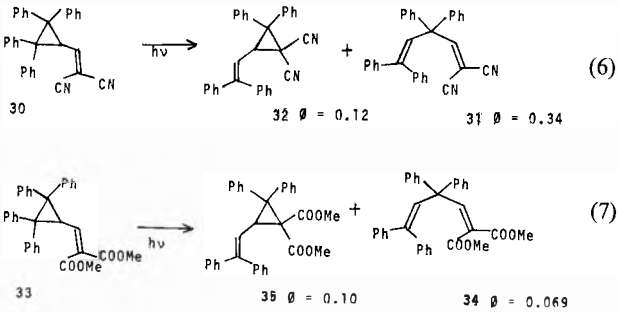
One might wonder whether the reaction proceeds only where the bicycling carbon is benzylic, since with one exception the above examples have involved bicycling of a benzylic moiety. A second example in which an isopropylidene carbon bicycles is shown in Equation 5 [13].



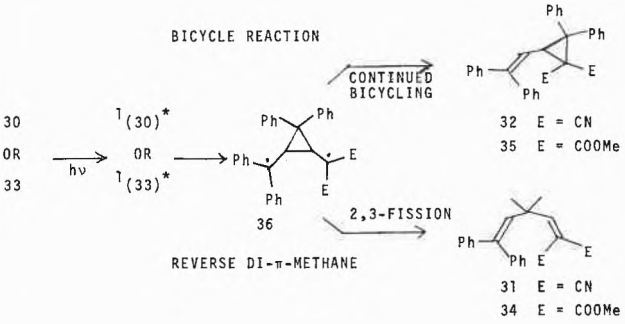
Interestingly, irradiation of the diene photoproduct **28** affords only the bicyclo[3.1.0] isomer **26** and no spiro isomer **27**. Since diradical **29** seems to be a likely species formed in both interconversions, this means that the same electronic state of **29** cannot be involved in the two irradiations.

One might also wonder if only bicyclic structures undergo the bicycle rearrangement in view of the examples given thus far. That a bicyclic structure is not a requisite for the bicycle rearrangement was found in some acyclic examples where the bicycling carbon moves along an acyclic chain of carbon atoms [9, 10]. In these examples, the migration is by a diphenyl-substituted carbon atom with formation of an isomeric vinylcyclopropane from the reactant as shown in Equations 6 and 7.

A further point of interest is that the bicycle processes are accompanied by "Reverse Di-π-Methane" rearrangements. We recognize these as the usual 2,3-fragmentation of the cyclopropyl-dicarbinyl 1,4-diradicals. Thus the reverse Di-π-Methane rearrangement comes from bicycling only part way down the chain as shown in Scheme III.



Scheme III: Mechanisms for Bicycling and Reverse Di-π-Methane Rearrangements.



We turn now to the question of reaction multiplicity. It is noted that the singlet excited states are responsible for the bicycling observed in the cases described above. Thus, in the various examples given, direct irradiation led to bicycling while sensitized irradiation, generating the triplet, led only to endo-exo stereoisomerization in those cases where such stereoisomers exist.

Now we are left with the matter of understanding the nature of the different electronic states of the cyclopropyldicarbinyl diradicals and how these account for different behavior. The evidence [4, 10, 14], deriving in part from theoretical investigations, suggests that it is most often, but not always [13], the first excited singlets (i. e. S_1) of the cyclopropyldicarbinyl diradicals which undergo the rearrangement to afford vinylcyclopropanes by bicycling while it is the ground states (i. e. S_0) which undergo the fission to 1,4-dienes.

The reasoning involved is seen most readily by considering one example, the rearrangement in equation 7. Here the we depict in Figure 4 only the highest two bonding MO's and the lowest two antibonding MO's, since these are most relevant. Also as the second part of Figure 4 we

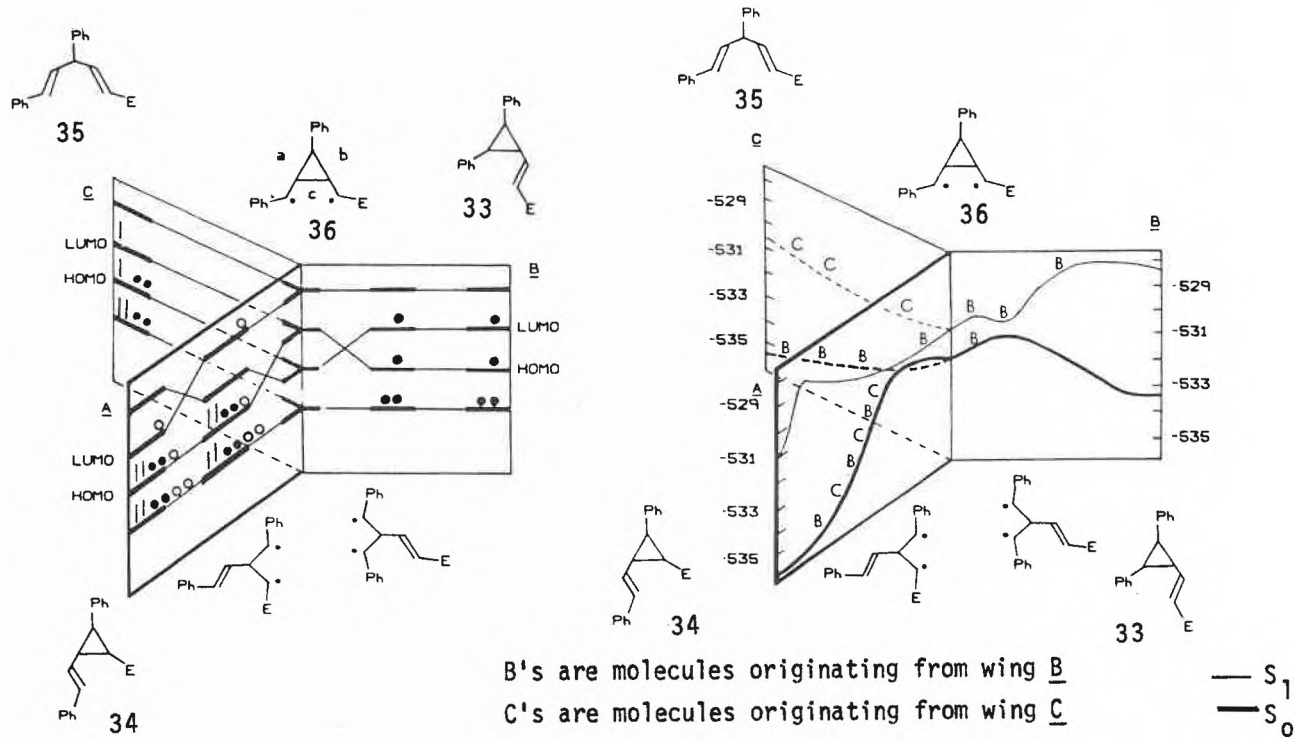


Fig. 4: MO and State Correlation Diagrams.

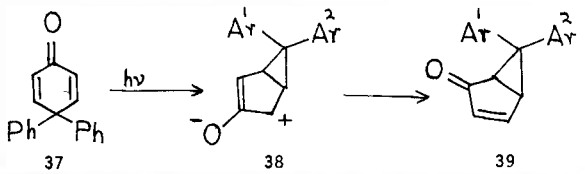
include the results of SCF-CI calculations which show the surfaces for the ground (i.e. S_0) and first singlet excited (i.e. S_1) states. The calculations were of the truncated variety where each pair of phenyl or ester groups was simulated by a single such group and where orbitals were used for those bonds which were either part of a chromophore or part of a bond formed, lost or modified during the reaction.

It is seen that there is a HOMO-LUMO crossing in wing *B* of the MO triptych, thus permitting [15] but not necessarily requiring internal conversion to the ground state cyclopropyldicarbinyl diradical represented by the axis of the triptych.

In parallel, the state diagram shows an approach of S_1 and S_0 at this point. To the extent that S_0 is formed it may be seen that the MO diagram permits formation of the ground state of the diene (i.e. the fragmentation product) in wing *C* of the triptych but not the bicycle product in wing *A*. This is seen also in the state diagram where no barrier exists between S_0 of the diradical and diene but a barrier is present between S_0 of the diradical and the bicycled product in wing *A*. Thus, the molecules originating in wing *B* and represented by "B"'s proceed nicely to diene if they lose excitation prior to the point where they become cyclopropyldicarbinyl diradicals.

Conversely, if excitation is not lost at the axis of the triptych, then it is seen from the MO correlation diagram that unexcited diene in wing *C* cannot be formed but that another HOMO-LUMO crossing occurs in wing *A* leading to ground state bicycled product. Inspection of the state diagram shows this in the form of an approach of ground and excited state surfaces (a crossing point [15], a bifunnel [10, 13], or funnel [16]) in wing *A* but not wing *C*. Having considered various examples of a photochemical rearrangement which is of a vinylcyclopropane to isomeric vinylcyclopropane in nature, we should note that a number of other photochemical rearrangements might be construed to have bicycle steps as part of their mechanisms. For example, and most related to the preceding examples, the Di-π-Methane rearrangement proceeds via a species which is a cyclopropyl-dicarbinyl diradical and whose last stage involves conversion of this diradical to a vinyl (or aryl) cyclopropane in a process which may, indeed, be considered to be a bicycle process. As an example, consider the conversion of species **36** to afford vinylcyclopropane **32** in Scheme III. Although it has not been discussed, the irradiation of diene **31** of Scheme III does afford vinylcyclopropane **32** in a Di-π-Methane rearrangement [9]. Similarly, **34** gives rise to **35**. In both cases an S_1 cyclopropyldicarbinyl diradical of the type **36** is involved and a bicycle step process is one way of writing this.

Similarly, the Type A rearrangement of 2,5-cyclo-hexadienones (e.g. **37**) involves a mechanism [17] in which β,



β-bonding in the n-π^* excited triplet leads eventually to a "Type A" zwitterion (e.g. **38**). It has been shown [18, 19, 20] that the rearrangement of such zwitterions to bicyclic enone photoproducts (e.g. **39**) is stereospecific with the endo group remaining endo and the exo group remaining exo. Note equation 8.

Clearly this is another example of a bicycle rearrangement.

In summary, it is still not certain just what limits are to be placed on the photochemical bicycle rearrangement. This is a challenge for the future.

Acknowledgment

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References

1 *H. E. Zimmerman, D. F. Juers, J. M. McCall,* and *B. Schröder:* J. Amer. Chem. Soc., *92,* 3474 (1970).
2 *H. E. Zimmerman, D. F. Juers, J. M. McCall,* and *B. Schröder:* J. Amer. Chem. Soc., *93,* 3662 (1971).
3 *H. E. Zimmerman* and *T. P. Cutler:* J. C. S. Chemical Communications, 232 (1978).
4 *H. E. Zimmerman* and *T. P. Cutler:* J. Org. Chem., *43,* 3283 (1978).
5 "Quantum Mechanics for Organic Chemists", *H. E. Zimmerman,* Academic Press, New York, 1975.
6 *H. E. Zimmerman, R. W. Binkley, R. S. Givens,* and *M. A. Sherwin:* J. Amer. Chem. Soc., *89,* 3932 (1967).
7 *H. E. Zimmerman* and *P. S. Mariano:* J. Amer. Chem. Soc., *91,* 1718 (1969).
8 *H. E. Zimmerman* in "Rearrangements in Ground and Excited States", Vol. 3, Edited by P. DeMayo, Academic Press, New York, 1980.
9 *H. E. Zimmerman, D. Armesto, M. G. Amezua, T. P. Gannett,* and *R. P. Johnson:* J. Amer. Chem. Soc., *101,* 6367 (1979).
10 *H. E. Zimmerman* and *R. E. Factor:* Tetrahedron, *37,* (1981), Supplement 1, 125–141.
11 (a) *H. E. Zimmerman, R. J. Boettcher, N. E. Buehler,* and *G. E. Keck:* J. Amer. Chem. Soc., *97,* 5635 (1975).
(b) *H. E. Zimmerman, R. J. Boettcher, N. E. Buehler, G. E. Keck* and *M. G. Steinmetz:* J. Amer. Chem. Soc., *98,* 7680 (1976).
12 (a) The definition of stereospecific is that originally suggested by the author in connection with "stereospecificity" and "stereoselectivity" (ref. 12b). This is the one also recommended by E. Eliel (ref. 12c). Thus where one stereoisomer is obtained from one reactant stereoisomer and the second is obtained from the second reactant stereoisomer, the reaction is termed "stereospecific" or as necessary (e.g.) "partially stereospecific". Conversely a stereoselective reaction is one where one stereoisomer is preferred independent of starting configuration or where there is no reactant stereochemistry. An older definition in which a reaction is stereoselective except where only one stereoisomer is formed (detected) means that whether a reaction is deemed stereospecific or stereoselective is a function of analytical technique, instrumentation and accuracy since the missing stereoisomer not detected by one investigator may be by a future one;
(b) *H. E. Zimmerman, B. S. Thyagarajan,* and *L. Singer:* J. Amer. Chem. Soc., *81,* 108–116 (1959);
(c) *E. Eliel:* "Stereochemistry of Carbon Compounds", McGraw-Hill, New York, 1977, 436.
13 *H. E. Zimmerman* and *R. E. Factor:* J. Amer. Chem. Soc., *102,* 3538 (1980).
14 *H. E. Zimmerman:* Topics in Current Chemistry, *100,* 45 (1982), Springer-Verlag, Heidelberg/New York, for further detail on theoretical approaches in photochemistry as well as a discussion of theoretical aspects of the Di-π-Methane rearrangement.
15 (a) *H. E. Zimmerman:* J. Amer. Chem. Soc., *88,* 1566 (1966);
(b) *H. E. Zimmerman:* Accts. Chem. Res., *5,* 393 (1972).
16 *J. Michl:* Mol. Photochem., 243, 257, 287 (1972).
17 *H. E. Zimmerman* and *D. I. Schuster:* J. Amer. Chem. Soc., *84,* 4527 (1962).
18 *H. E. Zimmerman, D. Döpp,* and *P. S. Huyffer:* J. Amer. Chem. Soc., *88,* 5352 (1966).
19 *H. E. Zimmerman* and *D. S. Crumrine:* J. Amer. Chem. Soc., *90,* 5612 (1968).
20 *H. E. Zimmerman, D. S. Crumrine, D. Döpp,* and *P. S. Huyffer:* J. Amer. Chem. Soc., *91,* 434 (1969).