

PARITY AND STEREOCHEMISTRY

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(Received 12 February 1974)

In 1965, Woodward and Hoffmann have given rules which correlate the stereochemistry of some organic reactions with orbital symmetry.¹⁻³

Very rapidly this theory proved itself to be very fruitful and of general application to a large number of organic reactions, the so-called pericyclic reactions.⁴

Since then, alternate formulations have been given by numerous authors, including Fukui,⁵ Dewar,^{6,7} Zimmerman,⁸⁻¹⁰ Oosterhoff,¹¹ Goddard,¹² Kaneko.¹³

Although all these authors have maintained (in a more or less explicit manner) the concept is of orbitals and of symmetry, Woodward and Hoffmann have summarized the whole of their findings in a selection rule which does explicitly include these two concepts.⁴

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

This rule is also valid even if a concerted pericyclic reaction is decomposed in elementary components.⁴ In their definition of "components", Woodward and Hoffmann have also defined *suprafacial* or *antarafacial* stereochemistry of components of any kind.

Woodward and Hoffmann rules have been constantly verified by experiment,⁴ at least when property used within the limits of their original framework. We have tried to give a simple expression of these rules, and to extent their field of application to other classes of organic reactions.

*The words symmetry-allowed or symmetry-forbidden introduce a concept which is not necessary to describe the experimental results.

†The electron-pairs "involved" in a reaction are those which have different connection in the starting molecule and in the reaction product.

In order to do this, we shall deal only with the basic concepts necessary to describe a molecule. More elaborate concepts were introduced to predict the steric course of pericyclic reactions. These concepts can be deduced from the classical ideas of organic chemistry,¹⁴ Lewis electron-pairs¹⁵ and Le Bel-van't Hoff tetrahedral carbon.^{16,17} In fact, the various "theoretical" descriptions of organic molecules are obtained from the classical description of a molecule by "simple" mathematical transformations.^{18,19} It is our opinion that the information content is not changed by such mathematical methods. We believe a consistent approach to organic chemistry is in ignoring these "theoretical" concepts and in restricting discussion to classical description of molecules and to experimental results. Woodward and Hoffmann generalized selection rule is in full agreement with this approach. Once the experimental results are known,⁴ Woodward-Hoffmann generalized rule can be entirely deduced from them without reference to "theory".

This rule can be simplified if we divide the number of electrons by two: i.e. if we consider the number of electron-pairs, $(4n)$ components have an *even* number $(2n)$ of electron-pairs, $(4n + 2)$ components have an *odd* number $(2n + 1)$ of electron-pairs.

The rule and experimental results display the following pattern of alternation, indicative of Boolean properties:

The structure of the Woodward-Hoffmann rules is such that it must be predicted whether a reaction is *allowed* or *forbidden*.*

Inspection of the experimental results shows that the classical factors which influence the reaction course obey a Boolean alternation:

(a) the number of electron-pairs involved† can be *even* or *odd*

(b) the steric course of a pericyclic reaction is such that:

there may be either *inversion* or *retention* on a given atom

reaction may be either *cis* or *trans* relative to a double bond

reaction may be either *supra* or *antarafacial* relative to a plane

rotations in polyenic systems may be either *disrotatory* or *conrotatory*.

For instance^{4b} changing the number of electron-pairs by unity changes, for example, a conrotatory reaction form allowed to forbidden and *vice-versa*.

Ground State	Conrotatory	Disrotatory
Excited State	Disrotatory	Conrotatory
	Even	Odd

number of electron pairs

Finally, the available experimental results show that photochemical reactions exist, which obey the complementary rule: allowed reaction in the excited state have the stereochemical course opposite to the ground-state reactions.

Extension of Woodward-Hoffmann rules

The pattern of alternation which appears in pericyclic reactions had already been noticed:

Ingold²⁰⁻²² has described the stereochemistry of some *linear* reactions by using the idea of *alternate motion* of electron-pairs.

Aromaticity also shows alternation: *Hückel-type systems²³ have $4n + 2$ electrons, i.e. an *odd* number of electron-pairs. Moebius-type systems²⁴ have $4n$ electrons, i.e. an *even* number of electron-pairs.

It is worth mentioning that Woodward²⁵ identifies aromaticity to a special case of pericyclic reaction. We can express his views in the following manner:

*This Boolean alternation has of course nothing to do with the bond length alternation observed in some aromatic systems.

†This is an interesting way of introducing some stereochemical limitations in mesomerism.

a system is aromatic if the formal exchange between two Kekule formulas is an allowed pericyclic reaction.[†] As a consequence, cyclobutadiene and systems with an *even* number of double bonds are aromatic in the excited state while benzene and systems with an *odd* number of double bonds are aromatic in the ground-state.

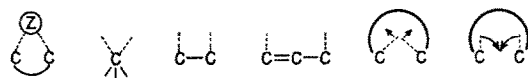
The alternating pattern resulting from both Woodward-Hoffmann rules and Ingold ideas, have led us to formulate a rule which summarizes their findings.

We have given the following formulation. For one of the present authors:^{26,27}

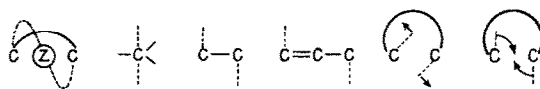
"Reactions involving an *odd* number of electron-pairs form or break bonds in the same half-space.

Reactions involving an *even* number of electron-pairs form or break bonds in the two different spaces."

In other words, reactions involving an *odd* number of electron-pairs have a *suprafacial* stereochemistry (this includes not only *suprafacial* migrations but also substitutions with *retention* of configurations, *cis* additions or eliminations, *syn* substitutions and *disrotatory* ring openings or ring closures). Similarly, reactions involving an *even* number of electron-pairs have an *antarafacial* stereochemistry (this includes not only *antarafacial* migrations but also substitutions with *inversion* of configuration, *trans* additions or eliminations, *anti* substitutions and *conrotatory* ring openings or ring closures).



suprafacial
odd number of electron-pairs



antarafacial
even number of electron-pairs

For the other author:²⁸ for an¹¹ allowed ground-state pericyclic reaction the sum of the number of electron-pairs involved and of the number of "odd processes" (i.e. inversions) must be "odd".¹¹

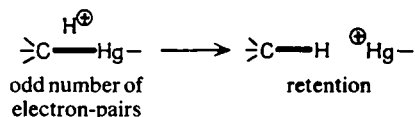
As a direct consequence, *odd* number of electron-pairs ground-state reactions involve an *even* number of *inversions*, *even* number of electron-pairs ground-state reactions involve an *odd* number of *inversions*. For both type of reactions, there is no restriction on the number of *retentions*.²⁹

This rule can be translated into a graph-system which uses the normal concept of electron displacement.³⁰

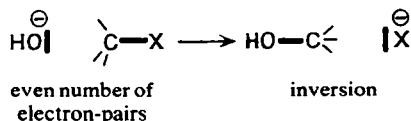
Application of parity rules

(1) *Pericyclic reactions.* In the case of pericyclic reactions, parity rules are only an equivalent formulation of Woodward-Hoffmann selection rule. As such they do not bring any additional information. We shall refer to Woodward-Hoffmann original paper³⁴ for a detailed analysis of pericyclic reaction which can be easily translated in terms of parity.

(2) *Ionic reactions.* Parity rules can be extended without any ambiguity to some substitution and addition reactions. For example, parity rules are in full agreement with the S_E2 substitution where only one electron-pair i.e. an *odd* number is involved:^{31a} there is no inversion.

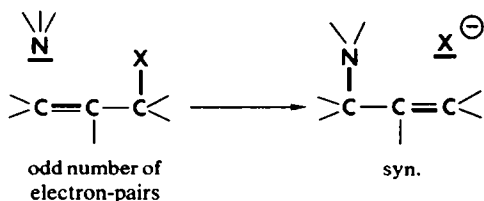


In the S_N2 substitution where two electron-pairs i.e. *even* number are involved: there is one inversion.^{31b}

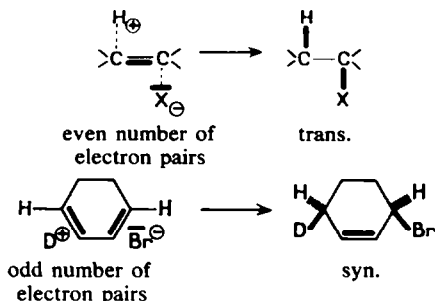


In Prime reactions where one more electron-pair is involved, the stereochemistry is reversed.

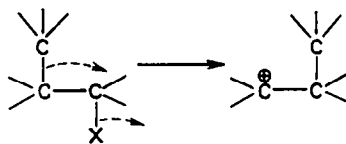
The S_N2' in which three electron-pairs (*odd* number) are involved is a *syn* substitution.³²



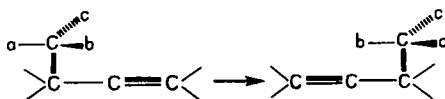
In the ionic 1-2-addition involving two electron-pairs (*even* number) the stereochemistry is *trans* and in the 1-4 addition where one more electron-pair is involved, the stereochemistry is reversed, giving a *syn* addition.³³



The Meerwein transposition in which two electron-pairs are involved should present only one inversion. The migrating carbon atom is not inverted whereas the receiving carbon is inverted.³⁴



In the 1,3 transposition there are also two electron-pairs (*even* number) and one inversion at the migrating carbon atom.³⁵



Limitation in the application of the parity rules

For pericyclic reactions the Woodward-Hoffmann rules and the parity rules are equivalent. In the whole field of applications both rules have the same limitation:

Parity rules being based upon the *number of electron-pairs* cannot be applied to radical reactions involving unpaired electrons.

Just as Woodward-Hoffmann rules, parity rules apply to *ground-state reaction*. It is possible to find some excited state-reactions which obey the complementarity rules.

Stereochemistry is defined relative to normal carbon stereochemical sites: tetrahedral C-atom for saturated systems or plane for unsaturated systems. Other types of sites deserve a special analysis: non tetrahedral sites (such as trigonal bipyramid or octahedron) or sites without apparent "objective" stereochemistry (such as monovalent or divalent atoms).

For instance, Woodward-Hoffmann rules, as well as parity rules, become ambiguous in cheletropic reactions.⁴⁶ We shall deal with these cases in a forthcoming paper.

Finally our parity rule, just as Woodward-Hoffmann generalized selection rule, deals only with concerted reactions. Although the concept of "concertedness" may be intuitive, an objective definition apparently still does not meet with general agreement. In our opinion, a reaction will be said to be concerted when all participating atoms stay at bonding distance from the beginning to the end of the reaction.³⁰

CONCLUSION

In this paper, we have shown that the correlation between parity of the number of electron-pairs and stereochemistry is not limited to pericyclic reac-

tions but can also be applied to concerted ionic reactions.

In our opinion, this analysis is not a mere coincidence: it is founded upon basic concepts of organic chemistry (Lewis formula and tetrahedral carbon atom) as well as the basic rules of electron movement (Walden inversion). These rules are in fact the projection into the organic chemistry theories of the more fundamental physical rules governing the dynamics of electrons and nuclei.

We can then safely rely upon classical concepts to study the stereochemistry of the products of concerted reactions and hopefully to get some ideas on their mechanism. In other words, the application of parity rules to concerted reactions seems a fruitful approach not only in order to rationalize known reactions but also in order to provide heuristic working hypotheses.

REFERENCES

- ¹R. B. Woodward and R. Hoffmann, *J. Am. Chem. Soc.* **87**, 395 (1965)
- ²R. Hoffmann and R. B. Woodward, *Ibid.* **87**, 4388 (1965)
- ³R. Hoffmann and R. B. Woodward, *Ibid.* **87**, 4389 (1965)
- ⁴R. B. Woodward and R. Hoffmann, *The Conservation of Orbital Symmetry* (Verlag Chemie, Weinheim/Bergstr., 1970); ^ap. 169, ^bp. 141, ^cp. 152
- ⁵K. Fukui, *Tetrahedron Letters* 2009 (1965)
- ⁶M. J. S. Dewar, *Tetrahedron* suppl. **8**, part 1, 75 (1966)
- ⁷M. J. S. Dewar, *Angew. Chem. Int. Ed. Engl.* **10**, 761 (1971)
- ⁸H. E. Zimmerman, *J. Am. Chem. Soc.* **88**, 1564 (1966)
- ⁹H. E. Zimmerman, *Accounts of Chemical Research*, **4**, 272 (1971)
- ¹⁰H. E. Zimmerman, *Ibid.* **5**, 393 (1972)
- ¹¹J. J. C. Mulder, L. J. Oosterhoff, *Chem. Commun.* 305 (1970)
- ¹²W. A. Goddard III, *J. Am. Chem. Soc.* **94**, 793 (1972)
- ¹³C. Kaneko, *Tetrahedron* **28**, 4915 (1972)
- ¹⁴W. Heisenberg quoted by W. G. Palmer, *A history of the concept of valency to 1930*. p. 125-165 Cambridge University Press
- ¹⁵G. N. Lewis, *Valence and the Structure of Atoms and Molecules*. Dover, New York (1966)
- ¹⁶J. A. Le Bel, *Bull. Soc. Chim. Fr* **22**, 337 (1874)
- ¹⁷J. H. van't Hoff (1874), see also *Ibid.* **23**, 295 (1875)
- ¹⁸H. Gunthard and H. Primas, *Helv. Chim. Acta* **39**, 1645 (1956)
- ¹⁹A. Graovac, I. Gutman, N. Trinajstić and T. Zivković, *Theor. Chim. Acta* **26**, 67 (1972)
- ²⁰M. L. Dhar, E. D. Hughes, C. K. Ingold, A. M. M. Mandour, G. A. Maw and L. I. Woolf, *J. Chem. Soc.* 2093 (1948)
- ²¹C. K. Ingold, Private communication (Burgenstock, 1966)
- ²²C. K. Ingold, *Structure and Mechanism in Organic Chemistry* (2nd Edition) p. 964. Cornell University Press (1969)
- ²³E. Hückel, *Z. Physik* **70**, 204 (1931)
- ²⁴E. Heilbronner, *Tetrahedron Letters* 1923 (1964)
- ²⁵R. B. Woodward, *Symposium on Orbital Symmetry Correlation in Organic Chemistry*. Cambridge (GB) 7-9 January (1969)
- ²⁶J. Mathieu, *C. R. Acad. Sci. Paris (C)* **274**, 81 (1972)
- ²⁷J. Mathieu, *Bull. Soc. Chim. Fr* 807 (1973)
- ²⁸A. Rassat, *C. R. Acad. Sci. Paris (C)* **274**, 730 (1972)
- ²⁹cf. R. W. Alder, R. Baker and J. M. Brown, *Mechanism in Organic Chemistry* p. 249, Wiley, London (1971)
- ³⁰A. Rassat, to be published
- ³¹E. L. Eliel, *Stereochemistry of Carbon Compounds* ^ap. 386. ^bp. 117. McGraw Hill New York (1962)
- ³²G. Stork and W. N. White, *J. Am. Chem. Soc.* **78**, 4609 (1956)
- ³³G. S. Hammond and J. Warkentin, *Ibid.* **83**, 2554 (1961)
- ³⁴Y. Pocker, P. de Mayo, *Molecular Rearrangement*, Vol. 1, p. 1. Interscience (1963)
- ³⁵J. A. Berson and G. J. Nelson, *J. Am. Chem. Soc.* **89**, 5503 (1967)