# Reprint

Stereochemistry of the Ozonolysis of Alkenes: Ozonide- *versus* Carbonyl Oxide-Control

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The reaction of ozone with alkenes in non-polar, aprotic solvents essentially proceeds according to the three-step mechanism proposed by *Criegee* [1], namely: (a) formation of primary ozonide *(1)*, (b) decomposition of *(1)* to aldehyde *(2)* and carbonyl oxide *(3)*, (c) recombination of the decomposition products to give the final ozonide *(4)*.
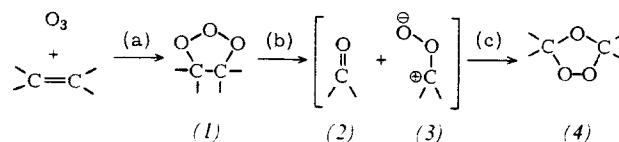
Of particular interest is the reaction step (b), whose energetics and stereochemistry could hitherto not be investigated because of the instability of *(1)* and *(3)*. Whereas *(1)* and *(4)* are each formed in a strongly exothermic reaction, the sign of the energy of reaction step (b) depends upon

Table 1. *Ab-initio* energies of reaction (in kcal/mol) calculated for the ozonolysis of alkenes [a].

| Reaction step	Ethene	Propene	2-Butene	
			trans	*cis*
(a)	− 49.2	− 50.5	− 50.7	− 51.2
(b)	13.7	6.4 [b]	1.2	− 0.2
(c)	− 63.1	− 58.3	− 55.9	− 55.1
(a + b + c)	− 98.6	− 102.4	− 105.3	− 106.5

[a] Correlation-corrected calculations with augmented 6-31G* basis according to the Møller-Plesset perturbation method (2nd order). The absolute energies for the parent compounds are: − 224.87683 (ozone), − 78.29431 (ethene), − 303.34952 *(1)*, − 114.17494 *(2)*, − 189.05283 *(3)*, − 303.32834 Hartree *(4)*. The alkyl effects were calculated according to the Hartree-Fock method. [b] Calculated for the formation of methylcarbonyl oxide and formaldehyde. The formation of acetaldehyde and carbonyl oxide is 2.3 kcal/mol more endothermic.

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the substituents at the alkene double bond. *Ab initio* calculations (Table 1) show that step (b) in the ozonolysis of ethene proceeds endothermally. The endothermic character of step (b) decreases on going to propene and 2-butene; in the case of 2,5-dimethyl-3-hexene, step (b) is distinctly exothermic[2]. The change in energy of reaction results from the different stabilization of *(1)*, *(2)* and *(3)* by alkyl groups[3-5].

If one assumes, in accord with the Hammond postulate[6], that the transition state is influenced by the product in endothermic reactions but by the educt in the case of exothermic reactions, then two alternatives can be distinguished for reaction step (b).

1) In the case of lower alkenes (ethene, propene, 2-butene) the stereochemistry of step (b) is essentially determined by the electronic properties of the carbonyl oxide that is formed. Quantum-chemical calculations on alkylcarbonyl oxides[4] show that, despite apparently unfavorable repulsion, the *syn*-isomers are 3—4 kcal/mol more stable than the corresponding *anti*-forms. This is ascribed to the attraction between a negatively charged terminal oxygen and positively charged H-atoms of the alkyl substituents. Through space π-bonding interactions (formation of a homoaromatic 6π-system) also contribute to stabilization of the *syn*-form[4].
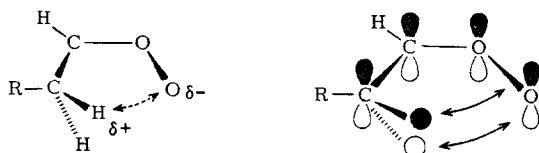
This effect should also play a role in the transition state of step (b) and should lead—irrespective of the configuration of *(1)*—to preferred formation of *syn-(3)*.

2) In the case of higher alkenes the conformational properties of the primary ozonide *(1)* determine the stereochemistry of step (b). The rules put forward by *Bailey et al.*[7] and *Kuczkowski et al.*[8] can be applied, namely *cis-(1)* preferably decomposes to *anti-(3)*, *trans-(1)* preferably to *syn-(3)*.

According to experimental[1,7,8] and theoretical findings[2] the following statements can be made about the stereochemistry of steps (a) and (c): The formation of *(1)* proceeds stereochemically with retention of the alkene configuration. The final ozonide *(4)*, on the other hand, is formed stereoselectively, *syn-(3)* being preferably incorporated in *trans-(4)*, *anti-(3)* preferably in *cis-(4)*.

The proportion of *cis*- and *trans-(4)* in the product mixture of the ozonolysis is substantially influenced by the stereochemistry of step (b). In the case of "carbonyl oxide-control" (ozonolysis of lower alkenes) predominantly *trans-(4)* is formed—irrespective of the configuration of the alkene[9]. In the case of "ozonide-control" (ozonolysis of higher alkenes) the *cis(trans)*-configuration of the alkene is essentially transferred to the final ozonide *(4)*. These quantum-chemical predictions explain the unusual stereochemistry of the ozonolysis of lower alkenes[1].

[1] *R. Criegee*, Angew. Chem. *87*, 765 (1975); Angew. Chem. Int. Ed. Engl. *14*, 716 (1975); cf. also *P. S. Bailey:* Ozonation in Organic Chemistry, Vol. I, Olefinic Compounds, Academic Press, New York 1978.

[2] *D. Cremer*, J. Am. Chem. Soc. *103*, 3619, 3627, 3633 (1981).

[3] *D. Cremer*, J. Chem. Phys. *70*, 1898, 1911, 1928 (1979).

[4] *D. Cremer*, J. Am. Chem. Soc. *101*, 7199 (1979).

[5] According to Hartree-Fock calculations with augmented 6—31 G* basis a methyl group stabilizes ethene by 3, the corresponding primary ozonide *(1)* by 4.3, the carbonyl oxide *(3)* by 11.6, formaldehyde by 9.3, and the final ozone *(4)* by 6.8 kcal/mol.

[6] *G. S. Hammond*, J. Am. Chem. Soc. *77*, 334 (1955); cf. also *A. R. Miller*, ibid. *100*, 1984 (1978).

[7] *L. Bauld, J. A. Thompson, C. E. Hudson, P. S. Bailey*, J. Am. Chem. Soc. *90*, 1822 (1968); *P. S. Bailey, T. M. Ferrell*, ibid. *100*, 899 (1978).

[8] *R. P. Lattimer, R. L. Kuczkowski, C. W. Gillies*, J. Am. Chem. Soc. *96*, 348 (1974).

[9] The formation of *cis*-cross ozonide (3,5-dimethyl-1,2,4-troxolane) in the ozonolysis of propene [8] cannot be explained in this way. Actually, however, only 4% of cross-ozonide has been observed in this reaction.