



A reinvestigation of the mechanism of epoxidation of alkenes by peroxy acids. A CASSCF and UQCISD study

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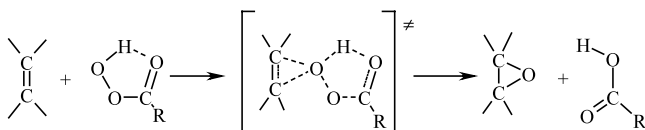
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Abstract—The transition state structure for the reaction of epoxidation of ethylene with peroxyformic acid is investigated at the CASSCF and UQCISD levels of theory. Both methods yield a highly unsymmetrical oxygen-addition transition state which has a diradical character. The value of the activation barrier calculated at the MCQDPT2(12,12)/6-311++G(d,p)//CASSCF(12,12)/6-311++G(d,p) correlated level (18.3 kcal/mol) is within the range of experimentally measured values. The predicted values of KIEs are in good agreement with the experimental data. © 2002 Elsevier Science Ltd. All rights reserved.

Since Prilezajew's discovery in 1908, the interaction of peroxy acids with different olefins is the basic synthetic method which leads to the formation of epoxides.¹ Bartlett proposed the most popular 'butterfly mechanism' of these transformations in 1957.² He suggested a mechanism in which the proton of the peracid is received by the carbonyl oxygen simultaneously with the attack on the olefin double bond by the terminal peroxy oxygen atom of the peracid.



According to Bartlett the mechanism of this reaction is concerted, and the transition state is symmetrical (**TS1**). The evidence supporting his suggestion has been provided by a number of experimental and theoretical investigations. Among them are the studies of kinetic isotope effects in the reactions of *m*-chloroperoxybenzoic (MCPBA) acid with 2,2,7,7-tetramethyl-*cis*-4-octene,³ 1-pentene,⁴ and ethylene⁵ and theoretical investigations of the interaction of ethylene,^{4,6} propene,^{4a,7} and isobutene⁷ and with peroxyformic acid performed by spin-restricted versions of the DFT,

QCISD, and CCSD(T) methods. Singleton and co-workers^{4a} have ruled out unsymmetrical structure for the epoxidation of alkyl-substituted alkenes based on comparisons of experimental values of secondary kinetic isotope effects (KIEs) for the epoxidation of 1-pentene by *m*CPBA in chlorobenzene with values calculated for model reactions (gas phase epoxidation of propene by performic acid) at the DFT and MP2 levels. These calculations have shown better correspondence of the KIEs calculated for the nearly symmetrical transition state at the RB3LYP level in comparison to the highly unsymmetrical transition state obtained at the MP2 level of theory.

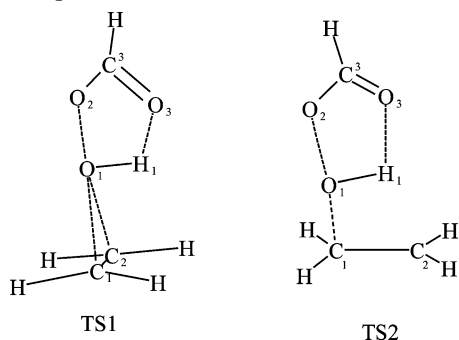
However, there are also some experimental and theoretical data that cannot be explained by the mechanism mentioned above. Based on an investigation of the secondary isotope effect in the reaction of 4-vinylbiphenyl with MCPBA, Hanzlik and Shearer⁸ conclude that the Bartlett's mechanism does not agree with their results. They suggest an unsymmetrical transition state (**TS2**) which involves an open chain structure. This point of view also has gained support from the quantum-chemical calculations performed at the Hartree-Fock (HF)⁹ and MP2 levels.¹⁰ However, more recently Bach and co-workers, based on KIEs of the reaction of 1,3-butadiene epoxidation by performic acid calculated at the MP2 level, concluded that epoxidation of conjugated alkenes proceeds via the moderately asynchronous transition state.⁷ These results should be taken with caution since the applied single-determinantal methods are not reliable for a description of diradi-

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cal structures. Interestingly, the mechanism of the Diels–Alder reaction cycloaddition also has been the subject of controversial interpretations which began in 1935 when Wassermann proposed the first model for the involved transition states, assuming a synchronic concerted process.¹¹ In 1936 Littmann postulated a two-step mechanism through a biradical intermediate.¹² Finally only in 1997 Ortuno et al. found experimental evidence of biradical mechanism in the Diels–Alder reaction of 5-methylene-2(5*H*)-furanes using ESR spin trapping techniques.¹³

Summarizing the current status of the experimental and theoretical studies of epoxidation reaction, one may conclude that the mechanism of this reaction, crucial for the basic synthetic methods is still unknown and that additional experimental and theoretical investigations are required.



In this work, a study of the interaction between ethylene and performic acid has been performed in the framework of the CASSCF and QCI computational techniques. The reason to choose these high level ab initio approximations is as follows. According to previous investigations^{4b,6} there is evidence suggesting that the transition state for the title reaction might have a diradical character (for example, the restricted HF solution for a symmetrical transition state located at the MP2/6-31G(d) level exhibits triplet instability⁶). In contrast, according to Bach and co-workers, at the B3LYP level transition states, the epoxidation of ethylene and its derivatives does not have singlet nor triplet instability.⁷ However, it was noted that contrary to the HF theory, DFT methods tend to avoid artificial spatial symmetry breaking.¹⁴ The single determinantal Kohn–Sham auxiliary state has different properties from the HF determinant. Therefore, a direct extension of such concepts as instability concerning the HF theory to the standard DFT functionals may not be absolutely rigorous.¹⁵ In summary, despite the fact that the DFT methods give good correspondence with high-level methods in the case of a single-configuration wavefunction,^{16,17} for systems with strong nondynamical electron correlations such as diradicals, these single determinantal methods may be inadequate, and only the quantum–chemical techniques which are potentially able to describe correctly the diradical state should be selected.^{16,17} For the present study we have chosen the CASSCF approximation which directly applies the multiconfiguration technique to a limited number of

molecular orbitals. We have also examined the QCI approximation which is formally based on one determinant wave function; however it uses multiconfiguration expansion to estimate the correlation correction.

The calculations reported here have been performed at the CASSCF level of theory¹⁸ as implemented in the GAMESS program¹⁹ using the following three sets of orbitals in the active space: (8,8) (eight electrons on eight orbitals), (10,10), and (12,12). The standard 6-31G(d) and 6-311++G(d,p) basis set have been used for unrestricted geometry optimizations of the local minima and transition state structures. Dynamic correlation has been estimated by carrying out the single-point MCQDPT2 (the multireference MP2) calculations²⁰ for the reference CASSCF optimized geometry. The inspection of the orbitals included in the active space of the Prelezajew's reaction transition state structure reveals that all of these orbitals could be involved in the forming and breaking of chemical bonds. In the (8,8) simplest case, the active space consists of the $\pi_{C_1=C_2}$, $\sigma_{O_1-O_2}$, $\pi_{C_3=O_3}$, $\sigma_{2p_y O_2-C_3-O_3}$, $\sigma_{O_1-O_2}^*$, $\pi_{C_1=C_2}^*$, $\sigma_{2p_y O_2-C_3-O_3}^*$, and $\pi_{C_3=O_3}^*$ bonding and antibonding orbitals. For the (10,10) and (12,12) active spaces, we have additionally included the $\sigma_{2p_x O_2-C_3-O_3}$ and n_{O_1} orbitals representing lone pairs, respectively. The nature of the stationary points on the potential energy surface have been verified by the calculations of the harmonic vibrational frequencies at the CASSCF(10,10)/6-31(d) level. The values of the activation barriers were corrected by zero-point energies calculated at the CASSCF(10,10)/6-31(d) level and scaled by a factor of 0.98.

To employ the QCI²¹ theory, the Gaussian 98 package²² has been used. Full optimization at the restricted (RQCISD) and unrestricted (UQCISD) levels of theory has been performed using the standard 6-31G(d) basis set. Single-point calculations have been carried out at the QCISD(T) level using the 6-31G(d), 6-311+G(d), and 6-311++G(d,p) basis sets. Zero-point energies for the QCI series of calculations have been obtained at the UQCISD/6-31G(d) level and scaled by a factor of 0.9537.

The initial geometry for the transition state search at the CASSCF/6-31G(d) level was the symmetrical spiro structure initially located as the saddle point at the RQCISD/6-31G(d) level (TS1). We have found that this structure is not the true saddle point on the potential energy surface calculated at the CASSCF(8,8)/6-31G(d), CASSCF(10,10)/6-31G(d), CASSCF(8,8)/6-31G(d), CASSCF(8,8)/6-311++G(d,p) and CASSCF(12,12)/6-311++G(d,p) levels of theory. It has been smoothly transformed to the highly unsymmetrical first-order saddle point TS2 characterized by the nearly planar orientation of peroxyformic acid relative to the ethylene double bond (see Table 1). It is characterized by the imaginary frequency of 871 cm^{-1} .

The optimization of the transition state structure at the UQCISD level generally yields the same results as those obtained by the CASSCF method. Starting from the initial RQCISD symmetrical structure, we have

Table 1. Geometrical parameters of the transition structure for the epoxidation of ethylene calculated at various levels of theory^a

Parameter	Unsymmetrical TS2						Symmetrical TS1	
	CASSCF/6-31G(d)			CASSCF/6-311++G(d,p)			UQCISD/	RQCISD/
	(8,8)	(10,10)	(12,12)	(8,8)	(12,12)	6-31G(d)	6-31G(d)	
O ₁ –O ₂	2.099	2.089 (2.103) ^b	2.049	2.006	1.937	1.827	1.866	
O ₁ –C ₁	1.869	1.866 (1.865)	1.837	1.848	1.761	1.845	2.006	
O ₁ –C ₂	2.628	2.627 (2.625)	2.604	2.584	2.505	2.380	2.006	
O ₃ –H ₁	2.121	2.118 (2.117)	2.091	2.140	2.077	1.871	1.681	
O ₁ –H ₁	0.955	0.955 (0.995)	0.955	0.967	0.977	0.993	1.010	
O ₂ O ₁ C ₁	165.2	165.2 (165.4)	164.6	162.3	159.9	151.2	159.6	
O ₁ C ₁ C ₂	106.4	106.6 (106.5)	106.5	104.9	104.2	94.0	70.0	
C ₃ O ₂ O ₁ H ₁	–2.9	0.3 (1.1)	–1.8	1.4	–0.3	–2.9	0.0	
H ₁ O ₁ C ₁ C ₂	–24.7	–15.3 (–18.8)	–19.1	–1.3	–0.3	–61.7	91.1	

^a Bond distances are in angstroms; bond angles are in degrees.

^b Calculated at CASSCF(10,10)/6-31G(d) level in the framework of the SCRf model with dielectric constant 8.93 which formally corresponds to the bulk of dichloromethane.

obtained a highly unsymmetrical transition state which is different from that obtained at the CASSCF level (see Table 1). It is characterized by one imaginary frequency (839 cm^{–1}) and has a spiro rather than a planar structure (see the values of the H₁O₁C₁C₂ angle in Table 1). The UQCISD transition state structure has remarkably short peroxy O₁–O₂ and C₁–O₁ bonds compared with the CASSCF level **TS2** species.

As expected, the optimized **TS2** structure has a diradical character. This conclusion has been obtained based on the remarkable depopulation of the HOMO calculated at the CASSCF level (for example, the natural orbital occupancies for the (12,12) active space are 1.96, 1.97, 1.84, 1.96, 1.95, 1.53, 0.54, 0.09, 0.08, 0.02, 0.02, and 0.02). The same statement is supported by an analysis of the spin densities calculated at the UQCISD level (total atomic spin densities are 0.5974, –0.9858, –0.5471, and 0.8791 for the C₁, C₂, O₁, and O₂ atoms, respectively, at the UQCISD/6-31(d) level). Because the contribution of the dominant configuration into the multiconfigurational wave function is 0.75, we conclude that the electronic structure of this transition state can be described correctly only by quantum–chemical methods which are based on multideterminantal approaches. Thus, it is not surprising that the results based on the single-determinantal restricted QCISD and B3LYP calculations^{4,6} differ dramatically when compared to the CASSCF calculations reported here.¹⁷

As mentioned above, the highly correlated ab initio methods have been applied to the title reaction in a previous study (Ref. 6). This study concludes that the value of the activation barrier is highly sensitive to the level of the chosen ab initio theory. The predicted values of the activation barrier have been in the range of 14.1 (B3LYP/6-31G(d)) to 29.1 kcal/mol (BD(T)6-31G(d)//MP2/6-31G(d)). Because of the solvent effects, the obtained values cannot be directly compared with the experimental data.²³ However, we would like to

mention that the activation barrier around 18 kcal/mol is in the range of the experimentally determined value.²⁴

To relate the results of our calculations to the experimental properties, we predicted KIEs for the title reaction. The value of the *d*₄ secondary DKIE (0.835) calculated at the CASSCF(10,10)/6-31G(d) level²⁵ for the epoxidation of ethylene by performic acid in dichloromethane is in excellent agreement with the experimental value which was obtained for the epoxidation of ethylene and *d*₄-ethylene by MCPBA acid in dichloromethane (0.830). It should also be mentioned that there is good agreement between the values calculated at the same level for primary DKIE (*k*_{OH}/*k*_{OD} = 1.10) and the experimental values obtained for the number of aliphatic alkenes (*k*_{OH}/*k*_{OD} = 1.05).⁵ The values of the KIE, calculated at the UQCISD/6-31G(d) level in the gas phase (0.800 and 1.07 for the *d*₄ secondary DKIE and the primary DKIE *k*_{OH}/*k*_{OD}, respectively), are also close to experimental results.

An analysis of the data presented in Tables 1 and 2 results in the following conclusions.

1. The geometry of the **TS2** structure virtually does not depend on the chosen set of active space for the CASSCF approximation, while the extended triple-zeta basis set yields tighter structure of **TS2** compared to the structure obtained with the 6–31G(d) basis set.
2. As shown in Table 2, the values of the barriers for the reaction proceeding through the diradical **TS2** are extremely sensitive to the chosen level of the electronic correlation. As is expected, the lowest value (18.3 kcal/mol) is obtained when the largest triple-zeta basis set (augmented by diffuse and polarized functions) is applied, and dynamic and non-dynamic correlations are included. This value is in the range of the experimentally measured values.

In summary, the application of ab initio techniques at the CASSCF and UQCI levels to the calculations of the mechanism of the gas phase Prilezajew's reaction has

Table 2. Activation barriers (in kcal/mol) for the epoxidation of ethylene with peroxyformic acid calculated at various computational levels^a

Computational level	ΔE^\ddagger
CASSCF(8,8)/6-31G(d)	22.2
CASSCF(10,10)/6-31G(d)	32.9
CASSCF(12,12)/6-31G(d)	37.5
CASSCF(8,8)/6-311++G(d,p)	37.3
CASSCF(12,12)/6-311++G(d,p)	26.0
MCQDPT2(8,8)/6-31G(d)//CASSCF(8,8)/6-31G(d)	26.3
MCQDPT2(10,10)/6-31G(d)//CASSCF(10,10)/6-31G(d)	28.9
MCQDPT2(12,12)/6-31G(d)//CASSCF(12,12)/6-31G(d)	24.8
MCQDPT2(8,8)/6-311++G(d,p)//CASSCF(8,8)/6-311++G(d,p)	14.3
MCQDPT2(12,12)/6-311++G(d,p)//CASSCF(12,12)/6-311++G(d,p)	18.3
UQCISD/6-31G(d)	32.5
UQCISD(T)/6-31G(d)//UQCISD/6-31G(d)	29.7
UQCISD/6-311++G(d,p)//UQCISD/6-31G(d)	31.3
UQCISD(T)/6-311++G(d,p)//UQCISD/6-31G(d)	28.3

^a Barrier heights are relative to the prereaction complex.

revealed the diradical character of the transition state. The transition state has an unsymmetrical open chain structure which can be described correctly only by the multiconfigurational wave function. The value of the activation barrier calculated at the highest MCQDPT2(12,12)/6-311++G(d,p)//CASSCF(12,12)/6-311++G(d,p) correlated level is in the range of the experimentally measured values. The predicted values of KIEs are in good agreement with experimental data.

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24. The value of the activation barrier in the amount of 14.7 kcal/mol in the reaction between the ethylene and peracetic acid can be estimated from the value of the ΔH^\ddagger in the amount of 11.1 kcal/mol^{23d} and five hundred-fold increasing of the rate constant in the reaction of dialkylalkens comparing to ethylene.^{23b}
25. DKIEs have been calculated according to Bigeleisen equations (Bigeleisen, J.; Mayer, M. G. *J. Chem. Phys.* **1947**, 15, 216) using ISOEFF98 program (Anisimov, V.; Paneth, P. ISOEFF98, Lodz, Poland, 1998) with frequencies scaled by 0.9. Influence of solvent has been taken into account by SCRF approach (Onsager, L. *J. Am. Chem. Soc.* **1936**, 58, 1486). Geometry of transition state and prereaction complex has been optimized at the same level of theory (see Table 1).