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Reexamination of orbital interactions in Diels–Alder reactions

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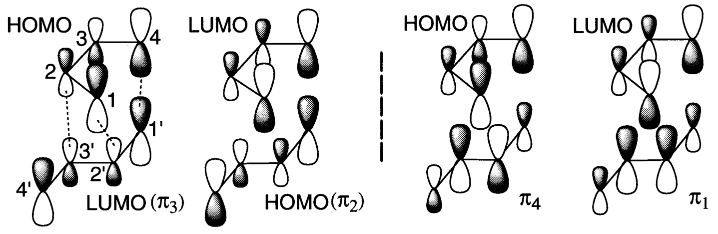
Abstract—An application of the perturbation theory to the [4+2] addition of butadiene has demonstrated that the effect of secondary orbital interactions should be much less significant than has been assumed within the frontier orbital scheme. This has been confirmed by a numerical analysis with respect to the *endo* transition state of the Diels–Alder reaction between butadiene and maleic anhydride. © 2002 Elsevier Science Ltd. All rights reserved.

The *endo* selectivity in the Diels–Alder reactions has been discussed by invoking many factors.[1] In particular, secondary orbital interactions (SOI) between the non-bonded atoms in a diene and a dienophile suggested by Hoffmann and Woodward have attracted the attention of chemists for a long time.[2] Apeloig and Matzner supported SOI for the Diels–Alder reaction between several dienes and cyclopropene.[3] On the other hand, Salvatella et al. argued against SOI in a recent account,[4] reexamining the experimental findings and citing some theoretical results.[1a,5] Since the concept of SOI has been applied in a number of studies, it is important to clarify the origin of such discrepancy.

A point to be noted here is that the concept of SOI is based on the frontier orbital theory, as sketched for two butadiene frames on the left-hand side of Scheme 1. In the interaction between the HOMO of one part and the LUMO of the other part, the pπ AO at C_2 of the diene and the one at $C_{3'}$ of the dienophile interact with the same sign as those for the interactions of the AOs at the reaction sites, giving rise to additional stabilization.[2] The higher unoccupied MO π_4 and the lower occupied MO π_1 of the dienophile were disregarded in that argument.

They do take part, however, in electron delocalization, as illustrated on the right-hand side of Scheme 1. These orbital interactions should be bonding at the reaction sites to facilitate the reaction and, accordingly, are antibonding between C_2 and $C_{3'}$. Contributions of π_1 and π_4 to the stabilization of the reacting system are smaller compared to those of the HOMO π_2 and the LUMO π_3, but π_1 and π_4 have large amplitudes on $C_{3'}$. A perturbation treatment within the Hückel MO scheme including all the π MOs tells us at once that the delocalization stabilization increases by 0.5–3.2%, when the resonance integral between C_2 and $C_{3'}$ is taken to be 3/10–1/2 of those between the reaction sites.[6] The C_2–$C_{3'}$ attraction is much weaker than that gained by the HOMO–LUMO interactions, in which the corresponding increase in the stabilization is as large as 15–25%.



Scheme 1.

Keywords: theoretical calculations; Diels–Alder reaction; secondary orbital interactions.

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In the Diels–Alder reaction of normal electron demand, dienophile plays an electron-acceptor part. The role of the LUMO of the dienophile will be strengthened. Let us look at the Diels–Alder reaction between butadiene and maleic anhydride. Full geometry optimization of the reactants and the transition states was performed at the B3LYP/6-31G** level by using the Gaussian 98 package.[7] The exchange potential in B3LYP was the three-parameter hybrid functional of Becke, and the correction potential was that of Lee, Yang and Parr.[8,9] The energy minima and transition states were verified by the vibrational analysis. The change in the Gibbs free energy in going from the reactant state to the transition state, $\Delta G^{\ddagger}$, at the temperature of 298.15 K in benzene was shown to be 129.5 and 124.6 kJ/mol for the *exo* and *endo* additions, respectively.[10,11]

To see what orbitals participate in electron delocalization at the *endo* transition state, we applied our interaction frontier orbital (IFO) scheme.[12] We expanded first the wave function of the reacting system in terms of electron configurations of the diene and dienophile fragments. Electron delocalization was presented by a mixing of the reactant-state electron configuration with electron configurations in which an electron was shifted from one fragment to the other. We then carried out transformations of MOs within the occupied MOs of one fragment and within the unoccupied MOs of the other fragment, to present electron delocalization in terms of paired interaction orbitals.[12] Two orbital pairs, (ϕ'_1; ψ'_1) and (ϕ'_2; ψ'_2), illustrated in Fig. 1 dominate electron delocalization in this system. The orbital ϕ'_1 is given by a linear combination of the occupied MOs of the diene and the orbital ψ'_1 by a combination of the unoccupied MOs of the dienophile. This pair of orbitals, denoted by pair 1, represents electron delocalization from the diene to the dienophile. On the other hand, ϕ'_2 is given by a hybrid of the unoccupied MOs of the diene and ψ'_2 is a hybrid of the occupied MOs of the dienophile. This pair, pair 2, stands for electron delocalization from the dienophile to the diene.

The occupied and unoccupied IFOs of the diene, ϕ'_1 and ϕ'_2, look similar to the HOMO and the LUMO of butadiene, respectively, with a mixing in of the σ-type MOs. This is natural, because butadiene is the smallest molecule that has a diene framework. On the other hand, the unoccupied and occupied IFOs of maleic anhydride, ψ'_1 and ψ'_2, resemble, respectively, the LUMO and the HOMO of ethylene, which is the smallest species having a C=C unit. In ψ'_1, a low-lying π-type unoccupied MO mixes strongly with the LUMO to *accumulate the bonding interactions on the reaction sites*. As a consequence, ψ'_1 shows practically no amplitude on the carbonyl carbons. This is understood easily by looking at the orbital interactions in Scheme 1. A combination of the π_3 and π_4 MOs in dienophile in-phase at the reaction sites, $c_3\pi_3+c_4\pi_4$ ($c_3>c_4>0$), leads to an intensified amplitude on $C_{1'}$ and $C_{2'}$, but results in a depression of amplitude on $C_{3'}$. An in-phase mixing of π_1 into π_2 at the reaction sites has the same effect. Actually, in the maleic anhydride part, two π-type MOs mix significantly with the HOMO to give ψ'_2. It shows the maximum amplitude on the reaction sites, but has very small amplitude on the carbonyl carbons. The *endo* preference calculated above does not come from SOI. Our analysis has revealed that the stereoselectivity is controlled by a balance of several energy terms, involving electrostatic attractions and the closed-shell repulsion.[13] The IFOs ψ'_1 and ψ'_2 are suited for describing the bond exchange in the dienophile that the C=C bond at the reaction site is loosened, but other bonds are not affected seriously upon electron acceptance or donation.[14]

In some other reactions, SOI will appear when several occupied or unoccupied MOs are taken into consideration. The controversy over SOI reminds us of the

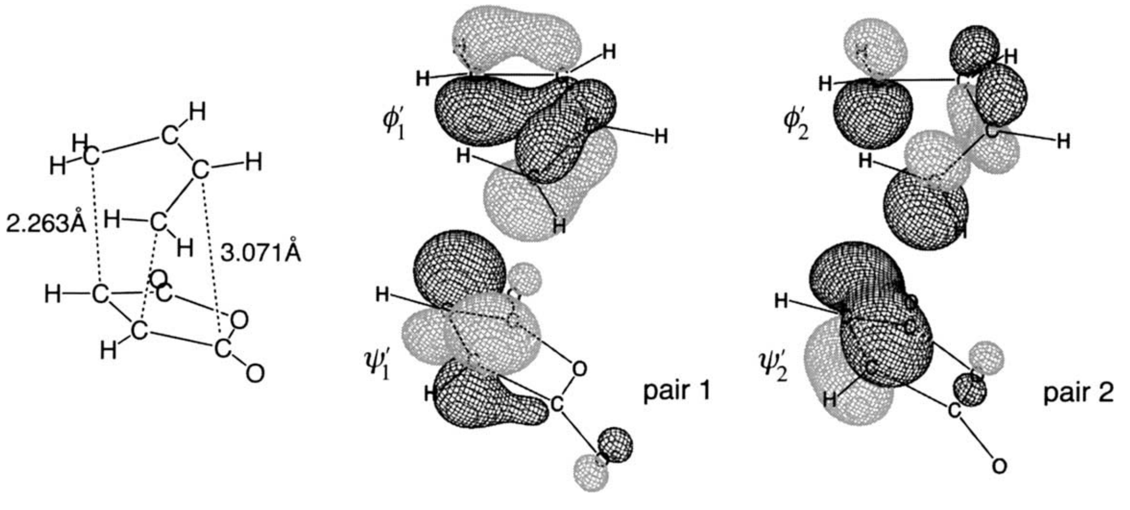

Figure 1. Two IFO pairs dominating electron delocalization at the *endo* transition state of the reaction between butadiene and maleic anhydride.

difficulty in applying the old frontier orbital theory, proposed half a century ago.

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