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PM3 Calculations on Cycloaddition Reactions of Diimide.

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Abstract: *Molecular orbital calculations for the reaction of E-diimide and butadiene show three stationary points for concerted cycloaddition. The lowest energy transition species is asymmetrical with the forming σ-bonds sufficiently similar in length for the reaction to be synchronous. exo-Addition of Z-diimide shows a symmetrical synchronous reaction pathway. endo-Addition reveals two valleys for concerted addition which are related by symmetry. The bond lengths of the forming σ-bonds are markedly different consistent with an asynchronous pathway. The calculations predict that endo addition is the most energetically favoured mode of addition for Z-diimide and butadiene.*

Diimide[1] (N_2H_2) is a short lived species best known as a reagent for the reduction of double bonds. There is some experimental evidence[2] that it undergoes Diels Alder cycloaddition when hydrogen transfer is disfavoured.[3] Substituted azo compounds are however highly reactive dienophiles in Diels Alder reactions and provide a convenient method for introducing two adjacent nitrogen atoms into a six-membered cyclic structure.

In order to understand the azo group as a dienophile the potential energy surface for diimide and *cisoid* butadiene has been examined as a model for azo cycloaddition. PM3[4,5] calculations were first performed for Z- and E- diimide and the transition state for the interconversion between the two isomers established. The results are shown in Figure 1. The E-form is predicted to be more stable[1f] and the barrier to E/Z interconversion is such that isomerisation will occur only slowly at room temperature.

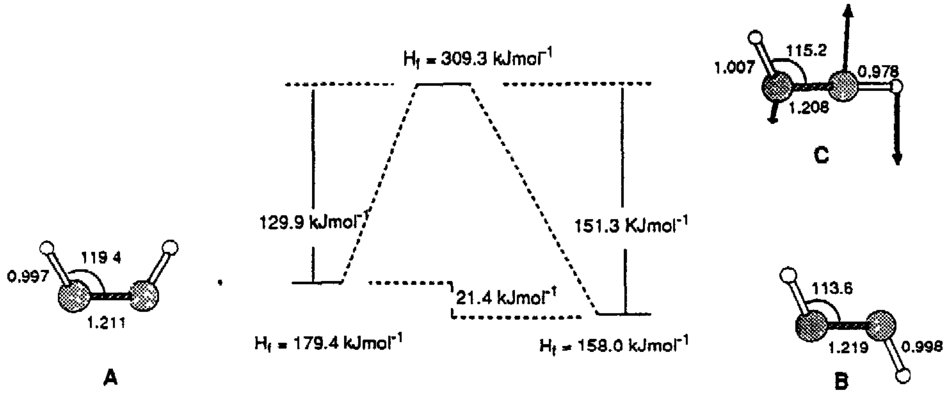


Figure 1. PM3 calculated geometries and heats of formation for Z- and E- diimide and the transition structure for E-Z interconversion including the major contributing vectors to the imaginary frequency.

Similar calculations were carried out for the product of cycloaddition of diimide and butadiene. The twist chair form of 1,2,4,6-tetrahydropyridazine[6] with the two NH's diaxial is the preferred conformation and is calculated to be 6.6 kJ mol^{-1} more stable than the conformation with the NH's diequatorial and 14.0 kJ mol^{-1} more stable than the conformation with one NH equatorial and the other axial.[7] Interconversion between the conformers is predicted to be facile.[8]

In order to investigate the transition species in the reaction of E- and Z- diimide with *cisoid* butadiene a potential energy surface was established by varying the distances R_1 and R_2 over the range 1.5-3.5 Å with full optimization of all the remaining geometrical variables.[9]

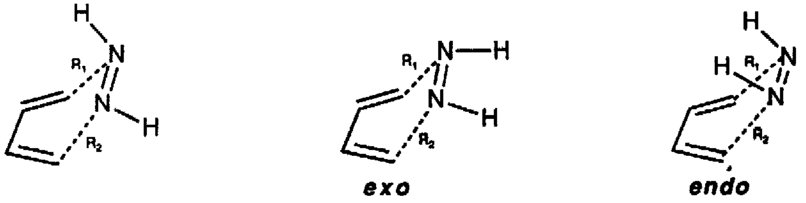
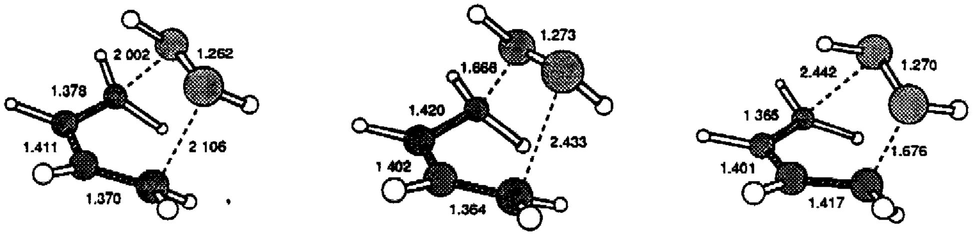


Figure 2. Definition of distances R_1 and R_2 used in the PM3 calculations of the Diels Alder additions of E- and Z- diimide and butadiene.

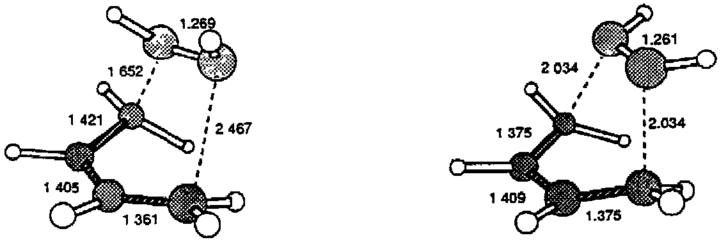
The PM3 potential energy surface for addition of E-diimide to butadiene shows a "ridge" between reactants and products with three "valleys" each with an associated stationary point[10] allowing for the concerted formation of 1,2,4,6-tetrahydropyridazine. The lowest energy transition species, A, is asymmetrical but with the forming σ-bonds sufficiently similar in length for the reaction to be considered synchronous.[11] The transition species, B and C, show a much greater difference in the length of the two forming σ-bonds at each termini. For any reaction proceeding via these transition states, while the reaction occurs in a single kinetic step, the addition can be considered to be asynchronous.[11] These two transition states are sufficiently close in energy to A for some fraction of the reaction to occur asynchronously.[12] For transition state C the shorter of the forming σ-bonds positions the *endo* NH between the terminal methylene hydrogens of butadiene. The relative heats of formation of these species, B and C, suggests that this is less favoured than in B which is lower in energy and where the lone pair of the corresponding nitrogen is positioned between the terminal methylene hydrogens.



A 442.2 kJ mol^{-1} B 444.8 kJ mol^{-1} C 453.1 kJ mol^{-1}

Figure 3. PM3 calculated stationary points for E-diimide and butadiene showing heats of formation

Addition of the Z-diimide to butadiene can occur *endo* or *exo*. The *exo* reaction exhibits a "ridge" between products and reactants. The "valley" connecting reactants and products corresponds to the forming σ-bonds each being the same length as the reaction proceeds. The transition state is symmetrical and corresponds to a synchronous reaction process. In contrast the potential energy surface for *endo* addition reveals two valleys for concerted addition which are related by the symmetry of the system. The bond length of each forming σ-bond is markedly different (0.82 Å) at the transition state. This shows that the reaction pathway is asynchronous and the formation of the two C-N bonds is not simultaneous.



endo 456.2 kJ mol^{-1} ***exo*** 471.0 kJ mol^{-1}

Figure 4. PM3 calculated stationary points for *exo* and *endo* addition of Z-diimide and butadiene showing heats of formation.

The PM3 calculations[13] reported above for the reaction of diimide and butadiene suggest that the Diels Alder addition of azo compounds may follow a significantly different reaction path from those which have been proposed for the Diels Alder addition of ethylenic and acetylenic dienophiles.[14] The calculations predict that the most energetically favoured mode of addition for Z-diimide and butadiene is in an *endo* configuration and although this reaction is predicted to occur with a single kinetic step, the new C-N bonds are not necessarily formed simultaneously.[15] Experiments[16] have shown that azo dienophiles frequently react with facially dissymmetric dienes with strikingly different facial selectivities to those of alkene dienophiles often paralleling acetylenic dienophiles. The calculations for the reactions of diimide suggest that the facial selectivity of azo dienophiles may result from the unsymmetrical nature of the transition state structure and the asynchronous character of the reaction. Steric and electronic interactions between azo dienophiles and facially dissymmetric dienes at the transition state can therefore be different from those with alkene and acetylenic dienophiles.

References and notes:

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2. In general conventional experiments attempting to trap diimide as a cycloaddition product with reactive dienes have failed and only products resulting from reduction have been isolated.
3. Gaviña, F.; Luis, S.V.; Costero, A.M.; Gil, P. *React. Polym.*, **1987**, *6*, 291. Gaviña, F.; Gil, P.; Palzón, B. *Tetrahedron Lett.*, **1979**, 1333.

4. Stewart, J.J.P. *J. Comput. Chem.* , **1989**, *10*, 209. All calculations were carried out with MOPAC, version 6.0. Quantum Chemistry Program Exchange (QCPE), Program Number 455, **1990.**
5. The results of previous studies (Grierson, L.; Perkins, M.J.; Rzepa, H.S. *J. Chem. Soc. Chem Commun.*, **1987**, 1779. Rzepa, H.S. *J. Chem. Res.*, (S), **1988**, 224.) using the AM1 molecular orbital method to examine pericyclic reactions where nitrogen atoms are involved in bonds which are formed or broken during the course of the reaction, led to the suggestion that the M_2 parameter which was reported as 2.1 Å for nitrogen in the core-core repulsion function is incorrect. The effect of this parameter was proposed to over-estimate of the internuclear repulsion between nitrogen and other atoms when separated by distances >1.9 Å, similar to the bond distances found in the transition species of pericyclic reactions. This has the effect of favouring asynchronous reaction pathways where the internuclear interactions can be minimized relative to those of synchronous ones. Agrafiotis and Rzepa[1h] have suggested that reducing the value of the M_2 parameter to ca. 1.6 Å will result in the AM1 method producing results which are more consistent with *ab initio* calculations. In PM3[4] the equivalent parameter to the AM1 M_2 (known as c_2 in the PM3 formulation) has a value of 1.716 Å and the results, in terms of reported average errors in calculated heats of formation for nitrogen containing compounds (especially nitro compounds), show a significant improvement over those for AM1. For this reason the calculations which will be discussed here will be from PM3 studies. The corresponding AM1 calculations have been carried out and the results appeared to be somewhat less convincing. McDonald, D.Q. PhD Thesis, University of Canterbury, **1991.**
6. Molecular mechanics calculations of the Diels Alder product 1,2,3,6-tetrahydropyridazine established that the twist chair conformation is approximately 40 kJ mol^{-1} more stable than the boat conformation.
7. Vibrational frequencies were calculated for these species and in each case it was established that they are minima on the PM3 potential energy surface.
8. The transition barrier for nitrogen inversion, converting the equatorial-axial to the diaxial conformer, is calculated to be low (30.2 kJ mol^{-1}).
9. Although the E-form of diimide is more stable the stereochemistry of reduction with diimide suggests that the Z-form has sufficient lifetime to be an important reactive species.[1]
10. For all the stationary points discussed here an approximate geometry was obtained by inspection of contour maps of the potential energy surface. The gradient minimization techniques in MOPAC were applied to these starting geometries to refine the transition state geometry. Vibrational frequencies were calculated for all the transition species and in every case these species were determined to have one imaginary vibrational frequency.
11. The following terms will be used as defined by Dewar: a concerted reaction takes place in a single kinetic step and a synchronous reaction is one in which all the bond making and bond breaking processes have proceeded to equal extents at the transition state. Dewar, M.J.S.; Olivella, S.; Stewart, J.J.P. *J. Am. Chem.Soc.*, **1986**, *108*, 5771.
12. This is a feature unique to the diimide system and no analogous stationary points have been identified from the many previously reported MO calculations of the Diels Alder reactions for a number of carbon based dienophiles.
13. The PM3 calculations reported here consider only the concerted pathways for diimide and butadiene. Experimental evidence (Clennan, E.L.; Earlywhite, A.D. *J. Am. Chem. Soc.*, **1987**, *109*, 7104.) for the Diels Alder reactions of substituted azo dienophiles, such as PTAD, suggests that non-concerted reaction pathways involving aziridinium imide species may be important. When appropriate aziridinium imide intermediates for the reaction of E-diimide and butadiene were examined with the PM3 method the calculated heat of formation for these intermediate species was found to be comparable to that calculated for the transition species described here. The non-concerted pathway involving these zwiterion intermediates is therefore not likely to be important for the reaction of diimide and butadiene. While the PM3 calculated heats of formation of the aziridinium intermediate suggest that these species are not important for this reaction, such intermediates may be stabilized by substitution on nitrogen. For cyclic azo compounds, such as PTAD, a highly asynchronous pathway involving such intermediates cannot be excluded.
14. Coxon, J.M.; Grice, S.T., Maclagan, R.G.A.R.; McDonald, D.Q. *J. Org. Chem.*, **1990**, *55*, 3804. Bach, R.D.; McDouall, J.J.W.; Schlegel, H.B.; Wolber, G. *J. Org. Chem.*, **1989**, *54*, 2931. Bernardi, F.; Bottoni, A.; Field, M.J.;Guest, M.F.; Hillier, I.H.; Robb, M.A.; Venturini, A. *J. Am. Chem. Soc.*, **1988**, *110*, 3050
15. This will have important consequences for understanding and modelling the reactions of azo compounds.
16. Coxon, J.M.; Maclagan, R.G.A.R.; McDonald, D.Q.; Steel, P.J. *J Org. Chem.*, **1991**, *56*, 2542.

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