J. Org. Chem. 1994, 59, 8058–8064

Ab Initio Study of the Thermal and Lewis Acid-Catalyzed Hetero Diels–Alder Reactions of 1,3-Butadiene and Isoprene with Sulfur Dioxide

D. Suárez,[†] J. González,[‡] T. L. Sordo,[†] and J. A. Sordo*,[†]

Departamento de Química Física y Analítica. Facultad de Química. Universidad de Oviedo, Julián Clavería 8, 33006 Oviedo, Principado de Asturias, Spain, and Instituto Universitario de Química Organometálica "Enrique Moles", Universidad de Oviedo, Julián Clavería 8, 33006 Oviedo, Principado de Asturias, Spain

Received May 2, 1994 (Revised Manuscript Received September 9, 1994[⊗])

Ab initio calculations at the MP2/6-31G*//RHF/6-31G* theory level provide data on the stereoselectivity and regioselectivity of the hetero Diels–Alder addition of sulfur dioxide to 1,3-butadiene and isoprene which are in good agreement with experimental evidence. Calculations indicate the importance of an electron-releasing methyl group in 1,3-butadiene (isoprene) as well as the remarkable role played by a Lewis acid catalyst. The existence of a CH--O electrostatic interaction is directly related to the stereoselectivity and regioselectivity of the cycloaddition.

Introduction

The Diels–Alder reaction is one of the most important and versatile transformations available to organic chemists for the construction of complex natural products, therapeutic agents, and synthetic materials of all kinds.[1] Such an importance fully justifies the remarkable interest found in the recent literature on the study of the different mechanistic aspects of this cycloaddition reaction by means of ab initio methodologies.[2]

Particularly interesting are the hetero Diels–Alder reactions, which are often key steps in stereoselective syntheses of natural products.[3] According to the ab initio calculations, hetero Diels–Alder reactions are predicted to take place through concerted but slightly asynchronous transition structures in a similar way to the all-carbon version.[2f–h,k]

Deguin and Vogel have reported that 1,3-dienes react with sulfur dioxide to give the Diels–Alder adducts.[4] It is well known that sulfur dioxide undergoes cheletropic reactions with conjugated dienes to give sulfolenes, but only few examples of Diels–Alder reactions were reported up to date.[5] We have recently reported ab initio results, at the RHF/6-31G*//3-21G* theory level, on the stereoselectivity and regioselectivity of the Lewis acid-catalyzed hetero Diels–Alder addition of sulfur dioxide to isoprene, in good agreement with experimental evidence.[6]

In this paper we present a theoretical study of the stereoselectivity and regioselectivity of the hetero Diels–Alder addition of sulfur dioxide to 1,3-dienes (1,3-butadiene and isoprene) with the purpose of understanding the decisive role played by both the substitution in the diene and the catalyst in this type of cycloadditions.

Method

Ab initio calculations have been carried out using the GAUSSIAN 92 package of programs.[7] Structures were fully optimized (at the restricted Hartree–Fock level of theory) with the 3-21G* and 6-31G* basis sets,[8] followed by vibrational frequency calculations which confirmed that reactants and transition structures (located by means of Schlegel's algorithm)[9] have zero and one imaginary frequency, respectively. In addition, single-point MP2/6-31G* calculations were carried out on all the RHF/3-21G* and RHF/6-31G* geometries.

The wave functions of the transition structures located in the present work were analyzed by means of a theoretical method based on the expansion of the MOs of a complex system in terms of the MOs of its fragments (using the geometry each fragment has in the corresponding transition structures) and the performance of the configurational analysis. Such a method has been developed by Fukui's group for bimolecular interactions[10] and extended by us to three-molecule interactions.[11] The basic ideas of the method can be summarized as follows: let us consider three species A, B, and C, which have closed-shell structures, and their composite system A-B-

---

[†] Departamento de Química Física y Analítica.

[‡] Instituto Universitario de Química Organometálica "Enrique Moles".

[⊗] Abstract published in *Advance ACS Abstracts*, November 15, 1994.

(1) Carruthers, W. *Cycloaddition Reactions in Organic Synthesis*; Pergamon Press: New York, 1990.

(2) (a) 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. (b) Houk, K. N.; Loncharic, R. J.; Blake, J. F.; Jorgensen, W. *J. Am. Chem. Soc.* **1989**, *111*, 9172. (c) Loncharich, R. J.; Brown, F.; Houk, K. N. *J. Org. Chem.* **1989**, *54*, 1129. (d) Bach, R. D.; McDouall, J. J. W.; Schlegel, H. B.; Wolber, G. J. *J. Org. Chem.* **1989**, *54*, 2931. (e) Birney, D. M.; Houk, K. N. *J. Am. Chem. Soc.* **1990**, *112*, 4127. (f) González, J.; Houk, K. N. *J. Org. Chem.* **1992**, *57*, 3031. (g) McCarrick, M. A.; Wu, Y-D.; Houk, K. N. *J. Am. Chem. Soc.* **1992**, *114*, 1499. (h) Bachrach, S. M.; Liu, M. J. *J. Org. Chem.* **1992**, *57*, 6736. (i) Jorgensen, W. L.; Lim, D.; Blake, J. F. *J. Am. Chem. Soc.* **1993**, *115*, 2936. (j) Li, Y.; Houk, K. N. *J. Am. Chem. Soc.* **1993**, *115*, 7478. (k) McCarrick, M. A.; Wu, Y-D.; Houk, K. N. *J. Org. Chem.* **1993**, *58*, 3330.

(3) Boger, D. L.; Weinreb, S. N. *Hetero Diels–Alder Methodology in Organic Synthesis*; Academic Press: San Diego, 1987.

(4) Deguin, B.; Vogel, P. *J. Am. Chem. Soc.* **1992**, *114*, 9210.

(5) Heldeweg, R. F.; Hogeveen, H. *J. Am. Chem. Soc.* **1976**, *948*, 2341. Durst, T.; Tetrault-Ryan, L. *Tetrahedron Lett.* **1978**, 2353.

(6) Suárez, D.; Sordo, T. L.; Sordo, J. A. *J. Am. Chem. Soc.* **1994**, *116*, 763.

(7) *Gaussian 92, Revision C*; Frisch, M. J.; Trucks, G. W.; Head-Gordon, M.; Gill, P. M. W.; Wong, M. W.; Foresman, J. B.; Johnson, B. G.; Schlegel, H. B.; Robb, M. A.; Replogle, E. S.; Gomperts, R.; Andres, J. L.; Raghavachari, K.; Binkley, J. S.; Gonzalez, C.; Martin, R. L.; Fox, D. J.; DeFrees, D. J.; Baker, J.; Stewart, J. J. P.; Pople, J. A. *Gaussian Inc.*, Pittsburgh PA, 1992.

(8) Pietro, W. J.; Francl, M. M.; Hehre, W. J.; De Frees, D. J.; Pople, J. A.; Binkley, J. S. *J. Am. Chem. Soc.* **1982**, *104*, 5039. Francl, M. M.; Pietro, W. J.; Hehere, W. J.; Binkley, J. S.; Gordon, M. S.; DeFrees, D. J.; Pople, J. A. *J. Chem. Phys.* **1982**, *77*, 3654.

(9) Schlegel, H. B. *J. Comput. Chem.* **1982**, *3*, 211.

(10) Fujimoto, H.; Kato, S.; Yamabe, S.; Fukui, K. *J. Chem. Phys.* **1974**, *60*, 572.

(11) Menéndez, M. I.; Sordo, J. A.; Sordo, T. L. *J. Phys. Chem.* **1992**, 96, 1185. López, R.; Menéndez, M. I.; Suárez, D.; Sordo, T. L.; Sordo, J. A. *Comput. Phys. Commun.* **1993**, *76*, 235.

0022-3263/94/1959-8058$04.50/0

C. We represent the MOs of A-B-C, ψ_g ($g = 1, 2, \cdots$ occ), by linear combinations of the MOs of A, B, and C as

$$\psi_g(1) = \sum_{i=1}^{\text{occ}} D_i(g)a_i(1) + \sum_{j=1}^{\text{unocc}} D_j(g)a_j(1) + \sum_{k=1}^{\text{occ}} D_k(g)b_k(1) + \sum_{l=1}^{\text{unocc}} D_l(g)b_l(1) + \sum_{m=1}^{\text{occ}} D_m(g)c_m(1) + \sum_{n=1}^{\text{unocc}} D_n(g)c_n(1) \quad (1)$$

where a_i, b_k, and c_m refer to the occupied MOs of systems A, B, and C, respectively, and a_j, b_l, and c_n to the corresponding unoccupied MOs. A calculation on the composite system A-B-C and on A, and B, and C, separately, renders the MOs ψ, a, b, and c in terms of the atomic basis functions used to compute A, B, and C. Then the coefficients $D_i(g)$, $D_j(g)$,$\cdots$,$D_n(g)$ in eq 1 can be obtained by solving linear simultaneous equations to fit the basis functions coefficients with respect to each MO of A-B-C.

To express the wave function of the complex, Ψ, in a chemically graspable form, we rewrite it by combination of various electronic configurations as

$$\Psi = c_o\Psi_o + \sum_q c_q\Psi_q \quad (2)$$

where Ψ_o is the state in which neither electron transfer nor electron excitation takes place, and Ψ_q stands for monotransferred configurations (one electron in an occupied MO in any of the three fragments A, B, and C is transferred to an unoccupied MO of a different fragment), monoexcited configurations (one electron in an occupied MO of any of the three fragments A, B, and C, is excited to an unoccupied MO of the same fragment), etc. The coefficients c_o and c_q in eq 2 are computed by means of mathematical expressions previously derived.[11] This method has proved useful for understanding the chemical features of complex formation from two or three chemically interacting systems,[12] thus being specially appropriate for the study of catalyzed bimolecular reactions as the ones dealt with in this paper.

Results and Discussion

Figures 1−3 depict the RHF/6-31G* transition structures corresponding to the two stereoisomers (endo, exo) of the reaction between 1,3-butadiene and sulfur dioxide (**TS1**, **TS2** in Figure 1), the two stereoisomers of the Lewis acid-catalyzed reaction (BH_3 was used as a model for the Lewis acid catalyst) between 1,3-butadiene and sulfur dioxide (**TS3**, **TS4** in Figure 1), the two regioisomers ("meta", "para") of the reaction between isoprene and sulfur dioxide to give both the endo and exo stereoisomers (**TS5**, **TS6**, **TS7**, **TS8** in Figure 2), and the corresponding regioisomers and stereoisomers for the reaction between isoprene and the $SO_2{-}BH_3$ complex (**TS9**, **TS10**, **TS11**, **TS12** in Figure 3). Figure 4 shows the transition structure corresponding to **TS5** (see Figure 2) as computed at the MP2(FC)/6-31G** correlated level. Table 1 collects the predicted activation energies and Table 2 the bond lengths of the two forming bonds (C−S and C−O) as well as the corresponding Mayer bond orders[13] for the twelve transition structures considered in this work (**TS1**−**TS12**). Table 3 shows the np-np overlap population corresponding to the two new bonds C-S and C-O in the endo and "meta"-endo transition structures. Table 4 presents the relative weights (from

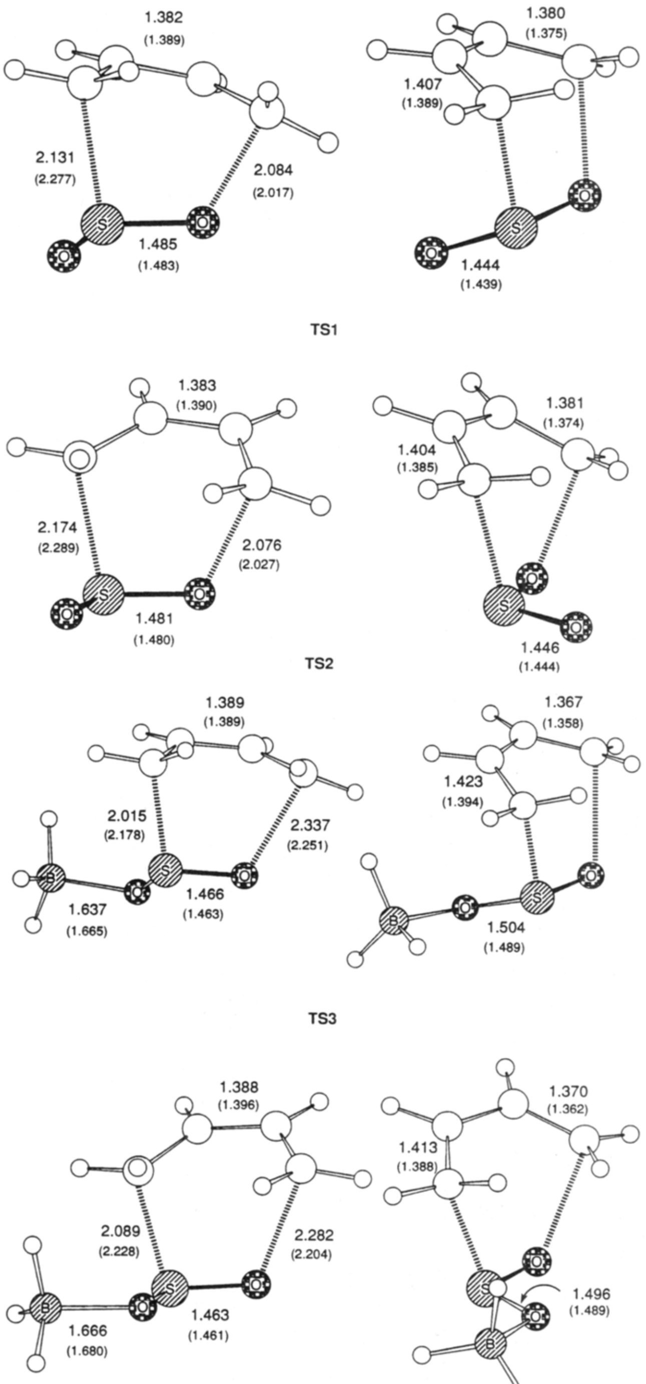

Figure 1. Transition structures, computed at the RHF/3-21G* (in parentheses) and RHF/6-31G* levels, for the (uncatalyzed and Lewis acid-catalyzed) cycloadditions of 1,3-butadiene (**TS1**−**TS4**) to sulfur dioxide. All distances in angstroms.

---

(12) Poo, R.; Sordo, T. L. *J. Chim. Phys.* **1987**, *84*, 755. López, R.; Sordo, J. A.; Sordo, T. L. *J. Mol. Struct.* (*Theochem*) **1992**, *254*, 443; Assfeld, X.; Sordo, J. A.; González, J.; Ruiz-López, M. F.; Sordo, T. L. *J. Mol. Struct.* (*Theochem*) **1993**, *287*, 193. López, R.; Sordo, J. A.; Sordo, T. L. *J. Chem. Soc. Chem. Commun.* **1993**, 1751. Assfeld, X.; González, J.; López, R.; Ruiz-López, M. F.; Sordo, J. A.; Sordo, T. L. *J. Comput. Chem.* **1994**, *15*, 479. Menéndez, M. I.; González, J.; Sordo, J. A.; Sordo, T. L. *J. Mol. Struct.* (*Theochem*) **1994**, *309*, 295.

(13) Mayer, I. *Int. J. Quant. Chem.* **1986**, *29*, 477.

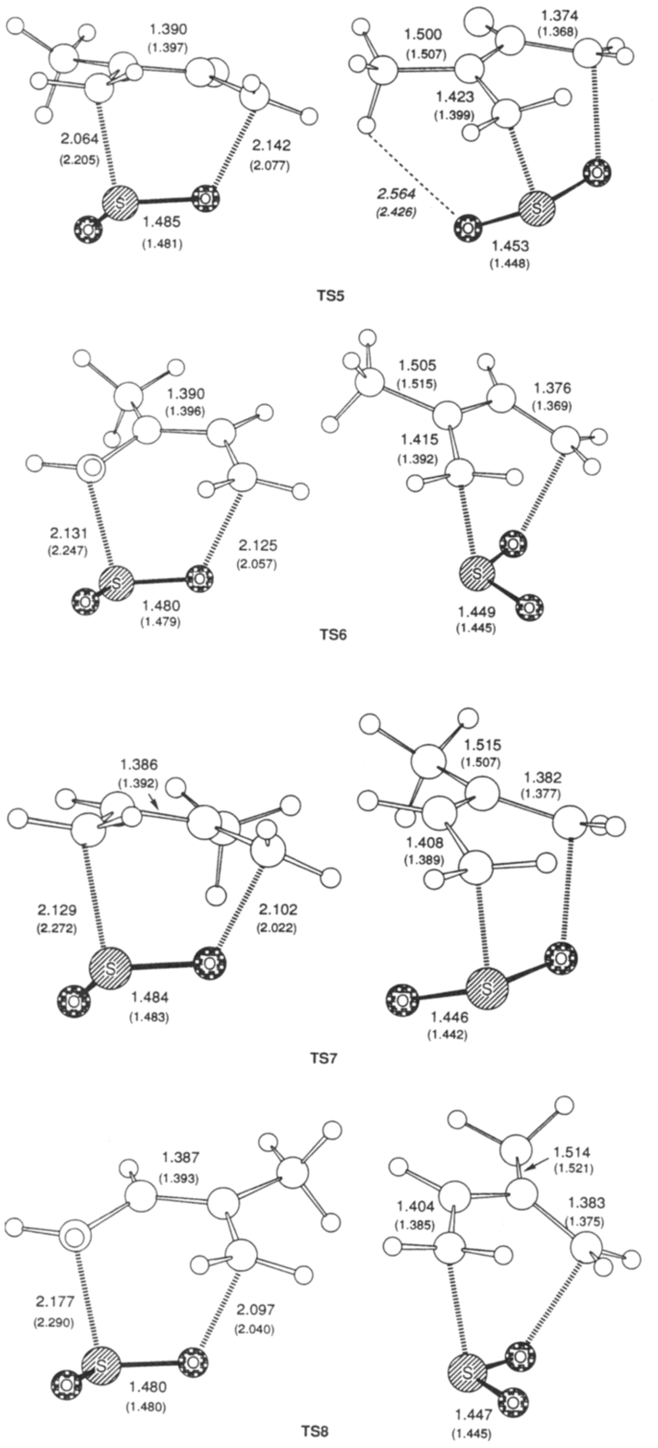

Figure 2. Transition structures, computed at the RHF/3-21G* (in parentheses) and RHF/6-31G* levels, for the uncatalyzed cycloadditions of isoprene (**TS5**−**TS8**) to sulfur dioxide. All distances in angstroms.

coefficients c_o and c_q in eq 2) of the most important fragment electronic configurations in the transition structures **TS1**, **TS3**, **TS5** and **TS9**. Finally, Table 5 collects the bond properties corresponding to the CH⋯O interaction present in the **TS5** and **TS9** structures.

The exploration we have carried out on the potential energy surfaces suggests a concerted but asynchronous mechanism for the $[_\pi 4_s + {}_\pi 2_s]$-cycloadditions of sulfur dioxide to 1,3-dienes, and it is in agreement with both experimental evidence[4] and recent theoretical studies on other hetero Diels−Alder reactions.[2f−h,k]

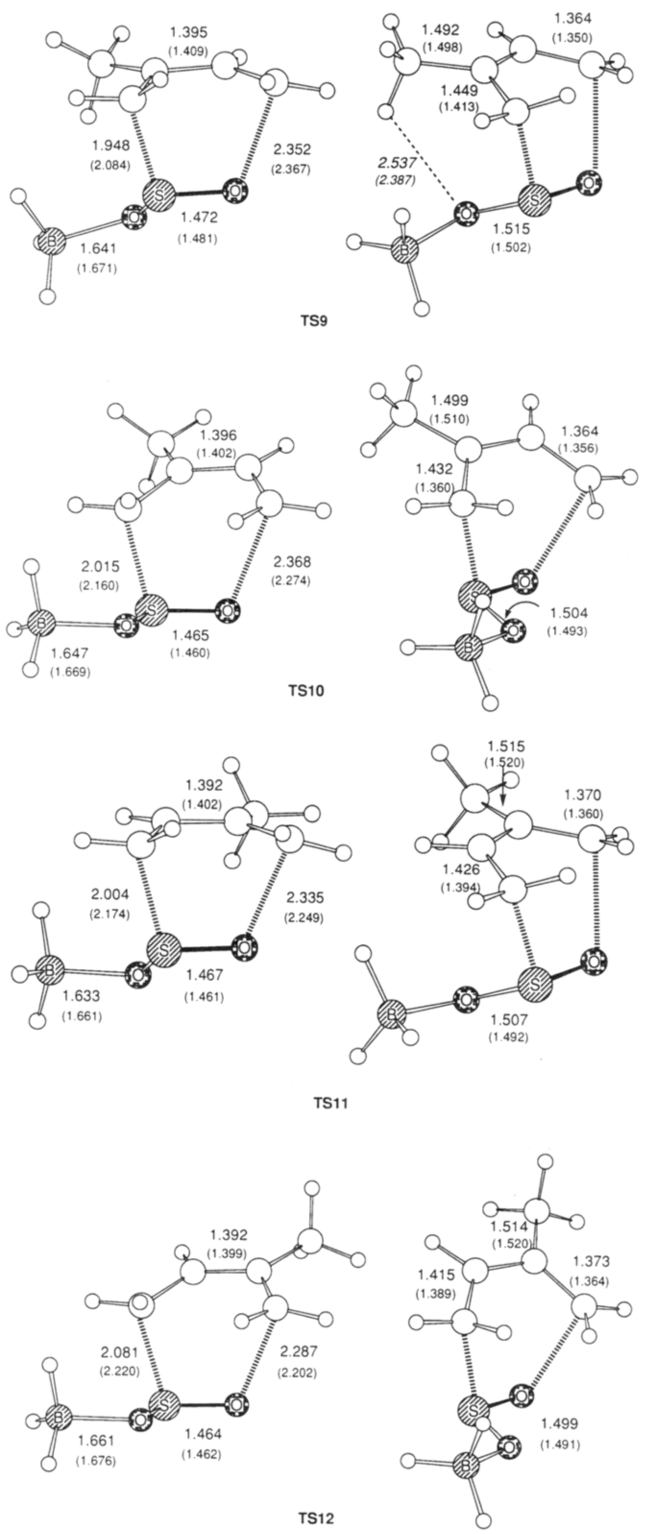

Figure 3. Transition structures, computed at the RHF/3-21G* (in parentheses) and RHF/6-31G* levels, for the Lewis acid-catalyzed cycloadditions of isoprene (**TS9**−**TS12**) to sulfur dioxide. All distances in angstroms.

Data collected in Table 1 show that, in general, there is an endo preference for the (uncatalyzed and catalyzed) reactions of 1,3-butadiene or isoprene with sulfur dioxide (an exception is provided by the MP2/6-31G*//RHF/6-31G* results on the uncatalyzed reaction of 1,3-butadiene with sulfur dioxide which predict a 1:1 mixture of endo and exo compounds). The activation energy becomes significantly lower in the case of isoprene (compare **TS1**

Table 1. Calculated Energies[a] (kcal/mol) of the Transition Structures and Products Relative to Reactants at the Different Theory Levels Used in This Work

		RHF/3-21G* optimized geometries			
transition structures		3-21G* (A)	3-21G*+ZPE[b] (B)	6-31G* (C)	MP2/6-31G* (D)
1,3-butadiene + SO_2 (endo)	**TS1**	22.3 (18.1)	24.6 (18.3)	32.9 (19.3)	14.6 (13.0)
1,3-butadiene + SO_2 (exo)	**TS2**	23.9 (19.7)	26.1 (19.8)	34.0 (20.4)	14.9 (13.3)
1,3-butadiene + $SO_2{-}BH_3$ (endo)	**TS3**	8.6 (4.4)	11.4 (5.1)	18.5 (4.9)	2.8 (1.2)
1,3-butadiene + $SO_2{-}BH_3$(exo)	**TS4**	11.4 (7.2)	14.0 (7.7)	22.3 (8.7)	4.2 (2.6)
isoprene + SO_2 ("meta"-endo)	**TS5**	18.0 (13.8)	20.0 (13.7)	29.2 (15.6)	11.6 (10.0)
isoprene + SO_2 ("meta"-exo)	**TS6**	22.2 (18.0)	23.8 (17.5)	32.3 (18.7)	14.1 (12.5)
isoprene + SO_2 ("para"-endo)	**TS7**	23.1 (18.9)	24.8 (18.5)	34.2 (20.6)	13.9 (12.3)
isoprene + SO_2 ("para"-exo)	**TS8**	25.0 (20.8)	26.5 (20.2)	35.5 (21.9)	14.4 (12.8)
isoprene + $SO_2{-}BH_3$ ("meta"-endo)	**TS9**	4.2 (0.0)	6.3 (0.0)	13.6 (0.0)	1.6 (0.0)
isoprene + $SO_2{-}BH_3$ ("meta"-exo)	**TS10**	8.2 (4.0)	10.2 (3.9)	18.4 (4.8)	3.2 (1.6)
isoprene + $SO_2{-}BH_3$ ("para"-endo)	**TS11**	8.8 (4.6)	10.9 (4.6)	19.0 (5.4)	1.7 (0.1)
isoprene + $SO_2{-}BH_3$ ("para"-exo)	**TS12**	12.0 (7.8)	14.0 (7.7)	23.1 (9.5)	3.6 (2.0)

	RHF/6-31G* optimized geometries			
	6-31G* (E)	6-31G*+ZPE[b] (F)	MP2/6-31G* (G)	ΔE_{rxn}[c] (H)
TS1	32.3 (16.6)	34.6 (15.2)	16.0 (12.9)	−12.7 (−7.6)
TS2	34.1 (18.4)	36.3 (16.9)	16.0 (12.9)	
TS3	20.6 (4.9)	24.9 (5.5)	4.5 (1.4)	−20.6 (−20.8)
TS4	24.6 (8.9)	28.5 (9.1)	5.0 (1.9)	
TS5	28.2 (12.5)	30.0 (10.6)	13.8 (10.7)	−13.9 (−9.1)
TS6	31.7 (16.0)	33.2 (13.8)	15.9 (12.8)	
TS7	32.3 (16.6)	34.0 (14.6)	15.6 (12.5)	−14.1 (−9.1)
TS8	35.1 (19.4)	36.6 (17.2)	15.8 (12.7)	
TS9	15.7 (0.0)	19.4 (0.0)	3.1 (0.0)	−22.2 (−22.8)
TS10	20.3 (4.6)	23.7 (4.3)	5.2 (2.1)	
TS11	20.9 (5.2)	24.6 (5.2)	3.8 (0.7)	−22.2 (−22.4)
TS12	25.3 (9.6)	28.6 (9.2)	4.7 (1.6)	

[a] Figures in parentheses in columns A–G are relative energies. [b] Corrected for zero-point energies. [c] HF/6-31G* energies (MP2/6-31G* energies are in parentheses).

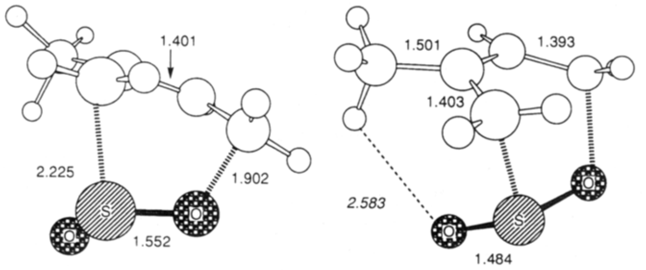

Figure 4. MP2(FC)/6-31G** ($\Delta E = 15.4$ kcal/mol) transition structure for the "meta"-endo isomer of the cycloaddition of isoprene to sulfur dioxide. All distances in angstroms.

Table 2. RHF/6-31G* Bond Lengths, *R* (Å) and Mayer Bond Orders, *B*, Corresponding to the Two Forming Bonds in the Twelve Transition Structures Collected in Table 1

	R(C–S)	*R*(C–O)	*B*(C–S)	*B*(C–O)
TS1	2.131	2.084	0.490	0.223
TS2	2.174	2.076	0.490	0.240
TS3	2.015	2.337	0.602	0.124
TS4	2.089	2.282	0.559	0.152
TS5	2.064	2.142	0.542	0.195
TS6	2.131	2.125	0.516	0.213
TS7	2.129	2.102	0.494	0.215
TS8	2.177	2.097	0.486	0.231
TS9	1.948	2.352	0.675	0.112
TS10	2.015	2.368	0.611	0.119
TS11	2.004	2.335	0.614	0.125
TS12	2.081	2.287	0.564	0.153

with **TS5**, and **TS3** with **TS9**). In addition, the Lewis acid-catalyzed reactions proceed through transition structures having substantially lower energies (compare **TS1** with **TS3**, and **TS5** with **TS9**).

These results are in good agreement with experimental evidence[4] which shows that the hetero Diels–Alder addition of sulfur dioxide to 1,3-dienes (a) obeys the Alder (endo) rule, (b) becomes too slow when no electron-releasing methyl group is present in 1,3-butadiene, and (c) requires the presence of a Lewis acid catalyst in order to proceed. Let us now analyze in detail all these aspects.

Stereoselectivity. The endo preference observed in Diels–Alder reactions has been ascribed to quite different factors.[14a] Particularly, Hoffmann and Woodward refined Alder's rule of "maximum accumulation of unsaturation" by proposing that secondary orbital overlap favors the endo product.[15] Steric effects have also been used to rationalize the endo preference[14] as well as a combination of steric effects and secondary orbital overlap.[16] Houk and co-workers have also suggested that electrostatic and van der Waals forces may promote endo cycloaddition just as they stabilize molecular charge-transfer complexes.[2c]

In the present case, we have detected very important electrostatic interactions (hydrogen bonding) in the transition structures **TS5** and **TS9**, which allow one to explain the observed endo preference. In fact, Figures 2 and 3 show that the distance between the sulfur dioxide oxygen not involved into the Diels–Alder cycloaddition and one of the hydrogens of the isoprene methyl group is 2.550 Å in **TS5** and 2.537 Å in **TS9**. Such distances are of the same order as those reported for CH⋯O hydrogen-bonded complexes.[17] Furthermore, a Bader-type density analysis[18] (see Table 5) revelaed the existence of a bond critical point between the two above

---

(14) (a) Sauer, J.; Sustmann, R. *Angew. Chem. Int. Ed. Engl.* **1980**, *19*, 779. (b) Brown, F. K.; Houk, K. N. *Tetrahedron Lett.* **1984**, 4609.

(15) Hoffmann, R.; Woodward, R. B. *J. Am. Chem. Soc.* **1965**, *87*, 4388.

(16) Fox, M. A.; Cardona, R.; Kiwiet, N. J. *J. Org. Chem.* **1987**, *52*, 1469.

(17) Desiraju, G. R. *Acc. Chem. Res.* **1991**, *24*, 290. Turi, L.; Dannenberg, J. J. *J. Phys. Chem.* **1993**, *97*, 7899.

(18) Bader, R. F. W. *Atoms in Molecules. A Quantum Theory*; Clarendon Press; Oxford, 1990. Bader, R. F. W. *Chem. Rev.* **1991**, *91*, 893.

Table 3. Analysis of RHF/6-31G* AO Overlap Population between all np AOs Centered on Atoms Involved in the New Bonds Being Formed (C–S and C–O Bonds) in the Transition Structures TS1, TS3, TS5, and TS9

		1,3-butadiene	
TS1	C-S/C-O	HOMO	LUMO
SO$_2$	HOMO	0.0049/0.0049	0.0126/0.0146
	LUMO	0.2045/0.0863	0.0482/-0.0232

Total np-np overlap population: 0.2096/0.0992

		1,3-butadiene	
TS3	C-S/C-O	HOMO	LUMO
SO$_2$-BH$_3$	HOMO	0.0004/0.0034	-0.0025/0.0252
	LUMO	0.2231/0.0707	0.0585/-0.0241

Total np-np overlap population: 0.2600/0.0540

		isoprene	
TS5	C-S/C-O	HOMO	LUMO
SO$_2$	HOMO	0.0055/0.0054	0.0117/0.0162
	LUMO	0.2318/0.0790	0.0409/-0.0214

Total np-np overlap population: 0.2311/0.0892

		isoprene	
TS9	C-S/C-O	HOMO	LUMO
SO$_2$-BH$_3$	HOMO	0.0011/0.0056	-0.0024/0.0226
	LUMO	0.2497/0.0637	0.0659/-0.0252

Total np-np overlap population: 0.3136/0.0482

mentioned atoms (the values of the electronic density at the critical points are 0.0089 and 0.0094 atomic units for **TS5** and **TS9**, respectively), thus corroborating the importance of the CH--O interaction present in **TS5** and **TS9**. Of course, neither **TS6–TS8** nor **TS10–TS12** structures are capable of forming CH--O hydrogen bonds and since no significant secondary overlaps have been found, it can be concluded that the CH--O electrostatic interaction plays a decisive role in the stabilization of the endo transition state relative to exo for the uncatalyzed and Lewis acid catalyzed Diels–Alder reactions between isoprene and sulfur dioxide. In order to test the validity of this important finding beyond the Hartree–Fock level of theory we carried out a MP2(FC)/6-31G** optimization of the **TS5** transition structure. Figure 4 depicts the result. The corresponding Bader-type MP2 density analysis[18] (see Table 5) confirmed the existence of a CH--O hydrogen bonding.

The justification for the endo preference in the case of the reaction between 1,3-butadiene and sulfur dioxide (**TS1** and **TS3**) becomes problematic since none of the aforementioned factors seems to be definitive. This remark conforms to the low (**TS3**) or even null (**TS1**) endo preference predicted by the MP2/6-31G*//RHF/6-31G* calculations (see Table 1).

Table 4. Relative Weights of Coefficients of the Most Important Fragment Electronic Configurations in the RHF/6-31G* Transition Structures TS1, TS3, TS5, and TS9

configurations[a]	TS1	TS5
AB	1.0000	1.0000
A$^-$B$^+$ (HOMO → LUMO)	0.4433	0.4818
A$^+$B$^-$ (HOMO → LUMO)	0.0294	0.0268
A$^+$B$^-$ (NHOMO → LUMO)	0.0368	0.0282
AB* (HOMO → LUMO)	0.1264	0.1265
AB* (HOMO → NLUMO)	0.0301	0.0287
A^{2-}B^{2+} (HOMO → LUMO/HOMO → LUMO)	0.0442	0.0513

configurations[a]	TS3	TS9
ABC	1.0000	1.0000
A$^-$B$^+$C (HOMO → LUMO)	0.5953	0.7056
A$^+$BC$^-$ (NNHOMO → LUMO)	0.0266	0.0256
A$^+$B$^-$C (HOMO → LUMO)	0.0137	0.0122
A$^+$B$^-$C (NHOMO → LUMO)	0.0146	0.0133
AB*C (HOMO → LUMO)	0.1683	0.1982
AB*C (HOMO → LUMO)	0.0258	0.0356
A*BC (HOMO → LUMO)	0.0125	0.0159
A^{2-}B^{2+}C (HOMO → LUMO/HOMO–LUMO)	0.0792	0.1088

[a] A: Dienophile. B: Diene. C: Catalyst.

Table 5. Bond Properties[a] for the CH--O Interaction in TS5 and TS9. R(CH--O), $\varrho(r_c)$, $\nabla^2\varrho(r_c)$ and ϵ are the Bond Length (Å), Electronic Density (au), Laplacian of Electronic Density, and Bond Ellipticity at the Bond Critical Point Corresponding to the CH--O Interaction Described in the Text

	R(CH--O)	$\varrho(r_c)$	$\nabla^2\varrho(r_c)$	ϵ
TS5 (RHF/6-31G*)	2.564	0.0089	0.0347	0.3118
TS5 (MP2(FC)/6-31G**)	2.583	0.0087	0.0312	0.3477
TS9 (RHF/6-31G*)	2.537	0.0094	0.0389	0.6001

[a] See ref 18.

Stereoselectivities of hetero Diels–Alder cycloadditions have also been related to electrostatic repulsions between the heteroatom lone pairs and the butadiene π electrons (exo-lone-pair effect).[2g,k] However, in the present case, the nature of the dienophile, with several lone pairs coming from sulfur and oxygen atoms, makes this type of analysis too complicated. Furthermore, neither the changes in the forming bond lengths (see Figures 1–3) nor the differences in activation energies (see Table 1) endo versus exo seem to be comparable with those reported in ref 2g,k.

It is noteworthy that the RHF calculations are consistent with the experimentally observed increase of stereoselectivity upon Lewis acid catalysis of Diels–Alder reactions.[19] Such an increase is less evident from the analysis of the MP2/6-31G*//RHF/6-31G* calculations.

Regioselectivity. The experimentally observed regioselectivity[4] is correctly predicted by the ab initio calculations. Indeed, Table 1 shows that the "meta" regioisomer is preferred for both the uncatalyzed (**TS5**) and the Lewis acid catalyzed (**TS9**) reactions of isoprene with sulfur dioxide. It is interesting to note that the MP2/6-31G*//RHF/6-31G* activation energy difference between the "meta" and "para" regioisomers corresponding to the Lewis acid-catalyzed reaction (**TS9** and **TS11**) becomes too small. Indeed, contrary to expectations,[19] this catalyzed reaction is less regioselective than the uncatalyzed reaction at this level of theory. Since the RHF/6-31G* calculations predict the expected behavior (see Table 1) it can be concluded that optimizations at the correlated level must be crucial to address this point.

---

(19) Houk, K. N. *J. Am. Chem. Soc.* **1973**, *95*, 4092, 4094.

The preference for the "meta" regioisomer for the reaction between isoprene and sulfur dioxide (or SO_2-BH_3 complex) can be rationalized in terms of the above mentioned CH⋯O interaction which clearly stabilizes the "meta" regioisomer relative to the "para" one since the distance between the methyl group and the oxygen of sulfur dioxide not involved in the cycloaddition in the latter is not short enough as to allow for hydrogen bonding (see Figures 2 and 3).

At this point it is interesting to make a comment on the importance of the presence of an electron-releasing methyl group in 1,3-butadiene. Table 3 shows that the new C–S bond is formed mainly through the HOMO(1,3-butadiene/isoprene)–LUMO(SO_2/SO_2-BH_3) interaction, the LUMO(1,3-butadiene/isoprene)–LUMO(SO_2/SO_2-BH_3)[20] having a smaller contribution, while the new C–O bond is formed mainly through both the HOMO(1,3-butadiene/isoprene)–LUMO(SO_2/SO_2-BH_3) and the LUMO(1,3-butadiene/isoprene)–HOMO(SO_2/SO_2-BH_3) interactions. When passing from **TS1/TS3** to **TS5/TS9**, Table 3 indicates that the importance of the HOMO(1,3-butadiene/isoprene)–LUMO(SO_2/SO_2-BH_3) interaction becomes greater for the C–S bond than for the C–O bond, thus justifying the observed increase of asynchronicity (see Table 2). On the other hand, the accentuation of the HOMO(1,3-butadiene/isoprene)–LUMO(SO_2/SO_2-BH_3) interaction leading to the formation of the C–S bond, when passing from **TS1/TS3** to **TS5/TS9** (see Table 3), is consistent with the parallel small increase observed in Table 4 for the relative weights of the corresponding coefficients of the monotransferred configuration A^-B^+ (HOMO(1,3-butadiene/isoprene) → LUMO(SO_2/SO_2-BH_3)), which results in the dominant configuration (apart from the zero one) according to the analysis described in the previous section.[11] This latter is, in turn, consistent with the computed (RHF/6-31G*) increase in the net charge transfer, from the diene to the dienophile, when passing from **TS1** (0.28 electrons) to **TS5** (0.32 electrons) or from **TS3** (0.46 electrons) to **TS9** (0.51 electrons). Stabilization of the above mentioned monotransferred configuration, A^-B^+, implies a stronger interaction between its diabatic curve and the one corresponding to the zero configuration, thus causing a lowering of the activation energy,[21] in agreement with data in Table 1 (**TS1** (ΔE = 16.0 kcal mol^{-1}) → **TS5** (ΔE = 13.8 kcal mol^{-1}); **TS3** (ΔE = 4.5 kcal mol^{-1}) → **TS9** (ΔE = 3.1 kcal mol^{-1})). This is in agreement with the experimental fact that the lack of an electron-releasing methyl group in 1,3-butadiene makes its cycloaddition to sulfur dioxide too slow.[4]

Lewis Acid Catalysis. Finally, let us analyze the role played by the catalyst. It has already been mentioned the effect of the presence of a Lewis acid catalyst on both the stereoselectivity and the regioselectivity. Now we will analyze the effect of such a catalyst on the activation barrier. It is well-known[6] that the presence of the catalyst enhances the electron acceptor character of the sulfur atom in sulfur dioxide, which causes a considerable increase in asynchronicity as can be seen in Table 2. Since the C–S bond is mainly formed through the HOMO(1,3-butadiene/isoprene)–LUMO(SO_2/SO_2-BH_3) interaction, the above facts suggest that an increase in the relative weight of the monotransferred configuration A^-B^+ for the Lewis acid-catalyzed reactions should be expected. Data collected in Table 4 fully corroborate this point. The significative increase of the coefficients of the monotransferred configuration A^-B^+ observed in Table 4 when passing from uncatalyzed to Lewis acid-catalyzed reactions (**TS1** → **TS3** and **TS5** → **TS9**) is consistent with a parallel notable increase in net charge transference from diene to dienophile detected when carrying out a Mulliken population analysis (**TS1** (0.28 electrons) → **TS3** (0.46 electrons) and **TS5** (0.32 electrons) → **TS9** (0.51 electrons)). The much more significant stabilization of the HOMO(1,3-butadiene/isoprene) → LUMO(SO_2/SO_2-BH_3) transference (A^-B^+ configuration in Table 4) by the Lewis acid catalyst allows for a stronger interaction between its diabatic curve and that of the zero configuration, thus causing the important lowering in the activation energy[21] observed in Table 1. The largest coefficient of this monotransferred configuration A^-B^+ corresponds to **TS9** (see Table 4), which, consequently, results in the most stabilized structure (see Table 1) in agreement with experimental evidence.[4]

Before ending let us make a brief comment on the different levels of theory used in this paper. Regarding geometries, Figures 1–3 show some of the most significative parameters of the RHF/3–21G* and RHF/6-31G* structures. In general, there is a reasonable agreement (extensive to the rest of geometrical parameters not collected in these figures for simplicity) with the exception of the bond lengths corresponding to the two new bonds being formed (C–S and C–O). Indeed, the RHF/3-21G* calculations predict much more asynchronous structures. Figure 4 shows that the optimization at the MP2(FC)/6-31G** correlated level renders forming bond lengths in good consonance with the RHF/3-21G* ones. On the other hand, figures in Table 1 clearly indicate that there is a very satisfactory agreement (even at the semiquantitative level in some cases) for the relative energies computed at the different RHF levels (see columns A–C and E–F in Table 1). This means that, for the kind of reactions dealt with in this paper, the relative activation energies computed at the RHF/3-21G* level are satisfactory approximations to the much more expensive RHF/6-31G* relative activation energies. It is also noteworthy that, in agreement with previous findings when studying quite different systems,[22] the MP2/6-31G*//RHF/3-21G* level of theory provides activation energies in reasonable agreement with those from MP2/6-31G*//RHF/6-31G* calculations (see columns D and G in Table 1) at a much lower computational cost.

Conclusions

The thermal and Lewis acid-catalyzed hetero Diels–Alder reactions of 1,3-butadiene and isoprene with sulfur dioxide have been studied ab initio at the MP2/6-31G*//RHF/6-31G* level. The importance of the presence of an electron-releasing methyl group in 1,3-butadiene (isoprene) as well as the remarkable role played by a Lewis acid catalyst in these reactions arising from the present study agree quite well with the experimental facts. Both aspects have been rationalized by analyzing the relative weight of the fragment configurations in

---

(20) Inagaki, S.; Fujimoto, H.; Fukui, K. *J. Am. Chem. Soc.* **1975**, *97*, 6108. Fukui, K. *Theory of Orientation and Stereoselection*; Springer Verlag: Berlin, 1975.

(21) Epiotis, N. *Theory of Organic Reactions*; Springer Verlag: Berlin, 1978. Shaik, S. S. *J. Am. Chem. Soc.* 1981, *103*, 3692. Shaik, S. S.; Schlegel, H. B.; Wolfe, S. *Theoretical Aspects of Physical Organic Chemistry*; John Wiley & Sons, New York, 1992.

(22) Wong, S. S.; Paddon-Row, M. N.; Li, Y.; Houk, K. N. *J. Am. Chem. Soc.* **1990**, *112*, 8679.

terms of which the wave function corresponding to any transition structure can be expanded according to a methodology recently developed. On the other hand, our calculations are consistent with the experimentally observed stereoselectivity and regioselectivity, which indicates the "meta"-endo to be the most favored isomer. Furthermore, it has been shown that the possibility of forming a hydrogen bond between the oxygen of sulfur dioxide which takes no part into the Diels–Alder bond formation and the substituents of 2-substituted butadienes can be directly related to the stereoselectivity and regioselectivity of these concerted cycloadditions.

Acknowledgment. The authors are indebted to the Centro de Proceso de Datos de la Universidad de Oviedo and to the CIEMAT (Ministerio de Industria y Energía) for computer time and thank the DGICyT (Spain) for financial support (PB91-0207-C02-02). D.S. also thanks the Ministerio de Educación y Ciencia for a grant.

Supplementary Material Available: Full geometries and energies of the eight transition structures **TS1–TS8** (8 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.