constants for the pH-rate profile were measured in solutions (I = 1.00) whose pHs had been adjusted with low concentrations of HCl (pH < 3.5), NaOAc (<1 × 10^{-3} M, pH 3.5-5.0), KH_2PO_4 (1 × 10^{-3} M, pH 5.0-7.8), $Na_2B_4O_7$ (<5 × 10^{-4} M, pH > 7.8). A constant check was maintained to detect any drift in the pH of the solutions. The values of k^1_{obs} and different pHs were fitted to eq 1 by using a generalized least-squares method.[85]

For aqueous solutions when there was a detectable amount of the enol form present, a equilibrium and the equilibrium constant K_{enol} (= E/K) was determined spectrophotometrically working at a wavelength at which only the keto form absorbed. A stock solution (30 μL) of a tautomeric mixture of known composition (determined by NMR spectroscopy) was injected into buffer (2 mL). The initial and final absorbance (A_0, A_∞), which correspond to the concentration of keto form in the stock solution and to that in the aqueous buffer at equilibrium, were recorded and K_{enol} was calculated from the equation $K_{enol} = (100 - x(A_\infty/A_0))/x(A_\infty/A_0)$ where x is the percentage keto form in the stock solution.

When K_{enol} is less than 0.02, the above technique cannot be used and the values were determined from the ratio of the rate constants for ketonization and enolization. The latter were determined by the iodine-trapping technique.[47] This was unsuccessful with furan-3(2*H*)-one as the disappearance of iodine was not zero order; presumably, there was direct attack of iodine on the double bond of the keto form.

The nonaqueous solutions the equilibrium constants were measured by ^{1}H NMR spectroscopy integrating the signals of the protons at C-2 of the enol and keto form after allowing equilibrium to be attained. Concentrations were normally 0.1-0.3 M and 2-fold dilution did not lead to any measurable change in the proportions of the two forms.

pK_as were determined spectrophotometrically by using a method based on that described by Albert and Serjeant.[86] The following wavelengths were used: 3-hydroxybenzofuran (327 nm), 3-hydroxybenzothiophene (368 nm), 3-hydroxyindole (380 nm), and 3-hydroxy-1-methylindole (417 nm). At these wavelengths the keto forms absorb strongly, the anions weakly, and enolic forms not at all so that

$$pK_a^{keto} = pH + \log [(d - d_i)/(d_m - d)]$$

and

$$pK_a^{enol} = pH + \log K_{enol} + \log [(d - d_i)/(d_m - d)]$$

Measurements were carried out at seven or eight pHs (solutions degassed) and the values were averaged (see Table V and Tables S10-13). These K_as are of course mixed constants.

General-acid-base catalysis was studied in buffer solutions by varying the concentrations of buffer while the ionic strength constant was maintained at 1.00 M with potassium chloride for a series of buffers with different buffer ratios. The values of k_{obs} for reaction in cyanoacetate, chloro acetate, and formate buffers were corrected for small variations in pH by plotting $k_{obs} - k_{H^+}a_{H^+} - k_{HO^-}a_{HO^-}k_{H_2O}$ versus ($[A^-] + a_{H^+}$] for each buffer ratio ($r = [HA]/[A^-]$), where $a_{H^+} = 10^{-pH}$, $a_{HO^-} = K_w/10^{-pH}$, and $[A^-]$ and [HA] are the concentrations of basic and acidic forms of the buffer that were added.[10] Plots of the slopes of these lines (k_{cal}) against r were themselves straight lines with slope k_{HA} and intercept k_{A^-}. Except for cyanoacetic acid, the strongest acid used, general-acid catalysis was much weaker than general-base catalysis, so although accurate values of k_{A^-} could be obtained, this was not always possible for k_{HA}.

The proportions of 3- and 4-thiolenone formed in the kinetic product on ketonization of 2-hydroxythiophene were determined at a number of acid concentrations in 90% CH_3CN-H_2O (v/v) by integrating the signals of H-5 of the 4-thiolenone (δ = 6.70) and of the CH_2 group of the 3-thiolenone (δ = 6.40) (Table S14). The percentages of 3-thiolenone formed in the H_3O^+ and H_2O catalyzed reactions were estimated to be 90 ± 5% and 50 ± 5%, respectively.

Registry No. 1a, 107637-99-0; **1b**, 520-72-9; **1c**, 480-93-3; **1d**, 107638-00-6; **1e**, 53820-83-0; **3a**, 29212-66-6; **3b**, 17236-59-8; **3c**, 29212-57-5; **3d**, 107638-08-4; **9b**, 496-31-1; **9e**, 615-13-4; **10a**, 20825-71-2; **12a**, 497-23-4; **12c**, 4031-15-6; **12d**, 13950-21-5; 3-acetoxy-1-methylindole, 3260-63-7; benzyl 3-hydroxypyrrole-3-carboxylate, 120475-60-7; 3-[(trimethylsilyl)oxy]benzofuran, 107638-01-7; 3-[(trimethylsilyl)oxy]benzothiophene, 107638-03-9; 3-[(trimethylsilyl)oxy]furan, 107638-06-2; 3-[(trimethylsilyl)oxy]thiophene, 107638-07-3; 3-[(trimethylsilyl)oxy]pyrrole, 107638-09-5; 1-methyl-3-[(trimethylsilyl)oxy]pyrrole, 107638-10-8; 1-indanone, 83-33-0; 3-[(trimethylsilyl)oxy]indene, 31928-64-0; 2-[(trimethylsilyl)oxy]benzothiophene, 107638-11-9; 2-[(trimethylsilyl)oxy]indene, 95683-63-9; 2-[(trimethylsilyl)oxy]furan, 61550-02-5; 1-(trimethylsilyl)-2-[(trimethylsilyl)oxy]pyrrole, 120475-58-3; 1-methyl-2-[(trimethylsilyl)oxy]pyrrole, 87884-52-4; 2-[(trimethylsilyl)oxy]thiophene, 83043-44-1; *trans*-2-bromo-1-indanol, 10368-44-2; *trans*-2-bromo-1-indanyl dimethyl orthoacetate, 120475-59-4.

Supplementary Material Available: Tables of first-order rate constants for the ketonization of hydroxy heterocycles in water (Tables S1-8), of the solvent effect on K_{enol} for 3-hydroxyindole (Table S9), of pK_a measurements (Tables S10-13), and of the percentage of 3-thiolen-2-one formed from 2-hydroxythiophene in acetonitrile-water mixtures at different acid concentrations (Table S14) (15 pages). Ordering information is given on any current masthead page.

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Experimental and Theoretical Studies of Substituent Effects on an Orbital Symmetry Forbidden Electrocyclization

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Lothar Franz,[1c] and G. N. Fickes[1c,d]

Contribution from the Department of Chemistry and Biochemistry, University of California, Los Angeles, Los Angeles, California 90024, the IBM Almaden Research Center, San Jose, California 95120, and the Department of Chemistry, University of Nevada, Reno, Nevada 89557. *Received August 8, 1988. Revised Manuscript Received January 12, 1989*

Abstract: The disrotatory electrocyclizations of several transient bridged *o*-xylylenes to form benzocyclobutenes has been investigated experimentally. Electron-withdrawing groups at the *o*-xylyene termini have large effects on the activation energy for this orbital symmetry forbidden reaction, while electron-donating groups have smaller effects. Ab initio quantum mechanical calculations on models of the transition structures of disrotatory electrocyclizations of butadienes reproduce these trends and have been used to develop a qualitative hypothesis to explain the unusual substituent effects found in the experimental study.

How do substituents influence the rates of orbital symmetry forbidden reactions? Little information is available to answer this question, because of the scarcity of examples of forbidden reactions. This question is related to the more general subject of substituent effects on allowed and forbidden pericyclic reactions. These are not known in general, except for cycloadditions such as the Diels-Alder reaction. Nevertheless, it is interesting and important to know these for many reasons. Carpenter predicted that the substituent effects on forbidden processes will be larger

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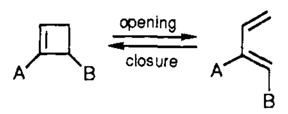
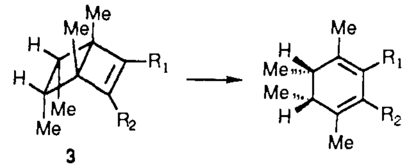
Table I. Estimated Substituent Effects on the Activation Energy of the Interconversions of Cyclobutene to Butadiene According to the Carpenter Model[a],[2]



position	group	conrotatory opening	conrotatory closure	disrotatory opening	disrotatory closure
A	none	0.0	0.0	0.0	0.0
A	polar[b]	0.192	0.118	−0.768	−0.842
A	conjugating	0.074	0.029	−0.131	−0.176
B	none	0.0	0.0	0.0	0.0
B	polar[b]	−0.638	0.356	−1.596	−0.604
B	conjugating	−0.398	0.118	−0.603	−0.087

[a] Units are β and are proportional to the predicted change in activation energy. A positive value indicates an increase in the activation energy, while a negative value indicates a decrease in the activation energy. [b] Polar groups can be either π donors or π acceptors. Both are predicted to have identical effects.

Table II. Activation Energies (kcal/mol) of Electrocyclizations of Several Substituted Bicyclo[2.2.0]hexenes[11]

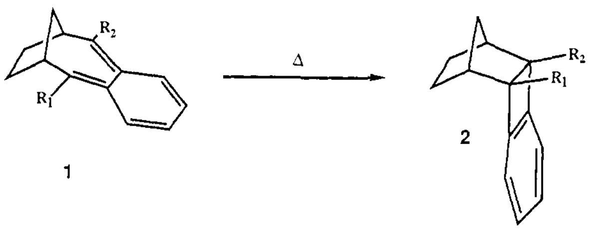


3

	R_1	R_2	$\Delta H^{\neq}$
a	Me	Me	36.8
b	CO_2Me	Me	32.3
c	CO_2Me	CO_2Me	28.4
d	CO_2Me	Ph	30.8

than analogous substituent effects on allowed reactions;[2] this theory predicts that both electron-donor and electron-acceptor substituents will influence the rate of a given reaction in the same way. Substituent effects on pericyclic reactions are also of practical interest in synthetic chemistry, because many such processes are used in natural-product synthesis. Substituent effects have been a focus of bioorganic interest in the chorismate–prephenate rearrangement,[3] since it is possible that an understanding of this reaction will provide a key to a broader understanding of the mechanism of enzyme action. Novel stereospecific substituent effects on the conrotatory electrocyclic reactions of cyclobutenes to butadienes have been predicted by theory and verified by experiment.[4-7]

Several experimental studies have given information about substituent effects on the disrotatory ring opening of cyclobutenes to form butadienes.[8] These reactions have been forced to be disrotatory by the imposition of geometric constraints. We undertook the study of the effect of substituents on the forbidden electrocyclic ring closure of substituted *o*-xylylenes, **1**, to give



1 **2**

benzocyclobutenes, **2**. As in previous studies, geometric constraints force the reaction to proceed via a Woodward–Hoffmann thermally forbidden disrotatory pathway. The activation energies for the thermal reactions of a number of substituted cases have been measured. Crude ab initio molecular orbital calculations on model systems have led us to propose an explanation for the substituent effects on these forbidden reactions; these results are used to extend the general theory of substituent effects on the butadiene–cyclobutene interconversions.[4-7]

Background

Carpenter's model for substituent effects on pericyclic reactions is based upon the simple, but daring, expectation that simple Hückel calculations on reactants and a simple model for transition states will give energy differences that parallel activation energies.[2] The transition state is treated as the isoconjugate cyclic hydrocarbon, following the definition by Dewar.[9] For electrocyclizations, the π energy of a 3-substituted cyclobutene is approximated as the π energy of ethylene plus the π energy of the substituent. The transition state of the allowed conrotatory reaction is approximated as a substituted Möbius cyclobutadiene, while that of the forbidden disrotatory reaction is taken as a substituted Hückel cyclobutadiene. Table I summarizes the predicted effect of substituents on the allowed and forbidden ring openings of cyclobutenes and ring closures of butadienes. Polar groups are either donors or acceptors, while conjugating substituents, like phenyl, are listed separately. The calculated values represent relative effects on the activation energy. Substituents with positive values are predicted to raise the activation energy, while those with negative values are predicted to lower the activation energy. For example, a polar group at position B (C_3 or C_4 of cyclobutene, C_1 or C_4 of butadiene) is estimated to lower the activation energy of the ring opening of cyclobutene for both the conrotatory (−0.638) and disrotatory (−1.596) processes. A polar group is predicted to raise the energy of the conrotatory ring closure (0.356) but to lower the activation energy of the disrotatory ring closure (−0.604). In general, substituent effects at position B (C_3 and C_4 of cyclobutene, C_1 or C_4 of butadiene) are expected to be as large or larger than those at position A (C_1 and C_2 of cyclobutene, C_2 or C_3 of butadiene).

Rondan and Houk have developed a theory to rationalize the rotational selectivity ("torquoselectivity")[10] of the conrotatory ring opening of 3-substituted cyclobutenes.[4] The more powerful donors, such as F, NH_2, and OH, lower the activation energy of ring opening by more than 9 kcal/mol and show a dramatic preference (>16 kcal/mol) for outward rotation over inward rotation. The effects on the ring-closure reaction are of the same order of magnitude as for the ring-opening reaction. Carpenter's predictions, although making no estimate of the rotational selectivity of the ring opening, indicate that the effects on the activation energy for conrotatory ring closure would be magnified in the disrotatory ring closures. Unfortunately, a lack of quantitative

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(4) Kirmse, W.; Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1984**, *106*, 7989. Rondan, N. G.; Houk, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 2099.

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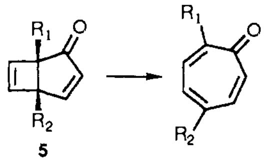
(7) Buda, A.; Wang, Y.; Houk, K. N. *J. Org. Chem.* **1989**, *59*, 2264.

(8) For a review of cyclobutene to butadiene interconversions, see: Marvel, E. *Thermal Electrocyclic Reactions*; Academic Press: New York, 1980; pp 124–213.

(9) Dewar, M. J. S.; Dougherty, R. C. *The PMO Theory of Organic Chemistry*; Plenum Press: New York, 1975.

(10) The term "torquoselectivity" was coined to describe the inherent preference for a substituent to rotate either inward or outward in the thermal conrotatory electrocyclic ring opening of 3-substituted cyclobutenes.[5] It might have a much more general application, however. Many processes in which C–C single bonds are formed or broken may be influenced by the preference of donors to rotate away from the breaking σ_{C-C} orbital and of acceptors to rotate towards the breaking σ_{C-C} orbital. Detailed computational and experimental studies of a variety of systems are under way.

Table III. Summary of Substituent Effects on Ring Openings of 3,6-Bicyclo[3.2.0]heptadien-2-ones[14]



5

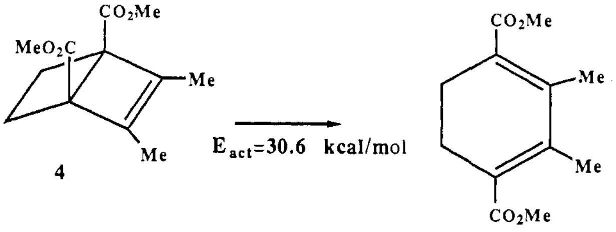
entry	R_1	R_2	T, °C^a
a	H	H	~350
b	$NHCH_3$	CN	−75
c	NH_2	CN	−50
d	$NHCH_3$	CO_2H	−44
e	OH	CHO	−42
f	$NHCH_3$	CO_2CH_3	−33
g	OH	CN	0
h	NH_2	C_6H_5	4
i	OH	CO_2H	10
j	OH	CO_2CH_3	10
k	OH	C_6H_5	55

^{a}Temperatures at which $t_{1/2}$ = 2 min.

experimental evidence has made it impossible to test this theory.

The powerful electron-withdrawing CO_2Me group has been shown to have a large effect on the activation energy of the disrotatory cyclobutene ring opening, regardless of the position of substitution. Experimental studies of substituent effects on the forbidden pathway for the disrotatory ring openings of tetramethyl-2-bicyclo[2.2.0]hexenes, **3**, show that a CO_2Me group located at either the 2- or the 3-position lowers the activation enthalpy of the disrotatory ring opening more than a phenyl group.[11] As summarized in Table II, the change from methyl to methoxycarbonyl causes an ~4 kcal/mol lowering of the activation enthalpy, while a phenyl only lowers the E_a by ~2 kcal/mol.

The activation energy of the ring opening of **4** is only 30.6 kcal/mol,[12] while the activation energy of the ring opening of

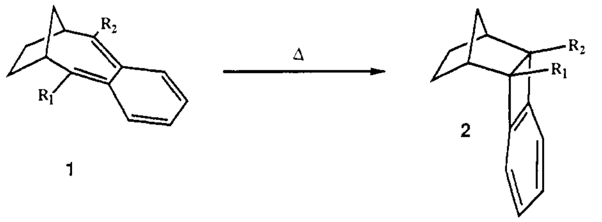


4

hexamethyl-2-bicyclo[2.2.0]hexene, **3a**, is approximately 37 kcal/mol.[11,13] If we assume that the methyl groups at C_5 and C_6 in hexamethyl-2-bicyclo[2.2.0]hexene have little effect on the activation energy of the reaction, then the replacement of the two methyl groups by two methoxycarbonyl groups at the 1- and 4-positions leads to a stabilization of about 6 kcal/mol. This 3 kcal/mol stabilization per methoxycarbonyl group is similar to the 4 kcal/mol stabilization found for the replacement of a methyl at the 2- and 3-positions in **3a** by a methoxycarbonyl group.[11]

The effect of donors on the reaction is less well studied, although qualitative results are available. Kobayashi et al. have shown that the rate of ring opening of substituted bicyclo[3.2.0]hept-3,6-dien-2-ones, **5**, is affected by substituents at C_1 (R_1) and C_5 (R_2) (Table III).[14] While many systems in which a donor and an acceptor are placed at C_1 and C_5 readily undergo ring opening at room temperature and below, the parent system **5a** is readily converted to tropone only at 350 °C.[15] It is particularly interesting that compound **5b** opens at −75 °C, showing that this combination of donor and acceptor substituents dramatically lowers the activation energy of ring opening.

Table IV. Experimental Activation Energies (kcal/mol) for the Conversion of **1** to **2**



1 **2**

entry	R_1	R_2	E_{acl}	ΔE^{rel}
a	Bu	Bu	30.0	
b	Cl	Cl	28.0	
c	H	^{t}Bu	25.5	0.0
d	Cl	^{t}Bu	23.6	−1.9
e	OMe	^{t}Bu	22.3	−3.2
f	Me	^{t}Bu	21.8	−3.7
g	$SiMe_3$	^{t}Bu	19.4	−6.1
h	CO_2Me	^{t}Bu	16.8	−8.7

While limited experimental data exist, there have been no computational studies of substituent effects on the disrotatory interconversions of cyclobutenes and butadienes. Theoretical studies of this disrotatory reaction have been concerned with location of a disrotatory transition structure and with estimation of the energy difference between the conrotatory and disrotatory transition structures. In fact, not all methods even agree that there is a disrotatory transition state for the thermal interconversion of cyclobutene to butadiene. Hsu and co-workers located an approximate disrotatory transition structure with an activation energy 14 kcal/mol above the conrotatory pathway at the 4-31G+CI//STO-3G level.[16] However, neither the conrotatory nor the disrotatory transition structure was fully optimized. Dewar et al. have used MINDO/3 to estimate the conrotatory–disrotatory energy difference of 17 kcal/mol,[17] although no harmonic frequency analysis was performed on the disrotatory transition structure. Bruelet and Schaefer have used a two-configuration SCF (TCSCF) procedure for the study of the conrotatory and disrotatory pathways for the interconversion of cyclobutene with butadiene.[18] The stationary point that they locate with C_s symmetry has two imaginary frequencies, indicating that this is not a transition structure. Extensive searches failed to locate a transition structure for the disrotatory interconversion of butadiene and cyclobutene.

Results and Discussion

Our investigations began with experimental studies of the disrotatory cyclizations of bridged *o*-xylylenes, **1**. Several 2,5-disubstituted benzotricyclo[4.2.1.$0^{2,5}$]nonanes were synthesized as described previously.[19] These were irradiated, as described in the Experimental Section, to produce the disubstituted bridged *o*-xylylenes as transient intermediates. The activation energy for the thermal cyclization to the 2,5-disubstituted *endo*-benzotricyclo[4.2.1.$0^{2,5}$]nonane was then measured. All of the substituted compounds form the endo adduct upon cyclization. The unsubstituted *endo*-benzotricyclo[4.2.1.$0^{2,5}$]nonane forms the exo product upon cyclization, precluding the direct comparison of activation energies with those for the substituted compounds.

Table IV shows the activation energies for the cyclizations of these bridged *o*-xylylenes. The approximate additivity of substituent effects for the conrotatory opening of cyclobutenes has been established previously.[4,20] We assume that a rough additivity

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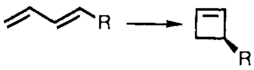
Table V. Calculated Substituent Effects (kcal/mol) on the Activation Energy of the Conrotatory Electrocyclization of 1-Substituted Butadienes To Form 3-Substituted Cyclobutenes[4]



substituent	E_{act}	$\Delta E^{rel_{act}}$
H	59.7	0.0
CH_3	59.2	−0.5
OH	53.0	−6.7
CN	57.9	−1.8
CHO	60.8	+1.1

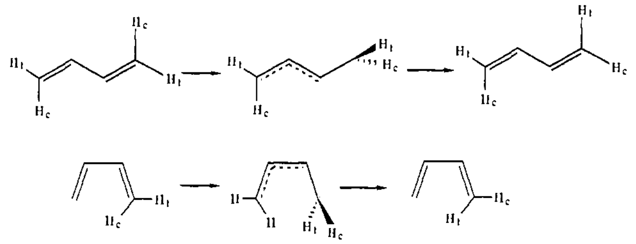
of substituent effects holds for the disrotatory transition structures as well. Because the activation energy of the parent system (**2**, $R_1 = R_2 = H$) could not be measured,[19] we have used entries **1a** and **1b** to estimate the steric effect of the *tert*-butyl group when compared with entries **1c** and **1d**. Because the chloro and butyl groups are sterically similar, but electronically different, the 4.5 kcal/mol lowering of the activation energy for either replacement of a chloro group by a tert-butyl group (**1b** vs **1d**) or replacement of the butyl groups by a *tert*-butyl and a hydrogen (**1a** vs **1c**) must be a reflection of the steric effect of the *tert*-butyl group, rather than a result of the electronic differences of the substituents. That is, the *tert*-butyl group destabilizes the *o*-xylylene and accelerates the reaction, as described later. The remaining data in Table IV can be used to determine the substituent effects for several substituents.

Table V compares substituent effects of the conrotatory ring closure reactions calculated at the 3-21G level.[5] This level of calculation has been shown to reproduce reasonably well the relative activation energies of the cyclobutene ring-opening reactions.[4-7] Comparison of the calculated substituent effects for the conrotatory ring closure of butadiene to cyclobutene, shown in Table V, with the experimentally determined disrotatory substituent effects points out some of the differences between the allowed and forbidden reactions. Although the data are somewhat limited, it appears that donor groups have a larger effect on the conrotatory transition structure than on the disrotatory transition structure and that acceptors have a much more pronounced effect on the forbidden disrotatory than on the allowed conrotatory transition structure. An alkoxy substituent lowers the activation energy for the forbidden ring closure by 3.2 kcal/mol, but hydroxy is calculated to lower the activation energy of the conrotatory ring closure by 6.7 kcal/mol. The CO_2Me group lowers the activation energy of the disrotatory ring closure by 8.7 kcal/mol, but the electronically similar CN group is calculated to lower the activation energy for the allowed process by only 1.3 kcal/mol.

The effect of the methyl group in **1** seems to be anomalous. The activation energy of the disrotatory ring closure is lowered by 3.7 kcal/mol, while the activation energy of the conrotatory ring closure is calculated to be lowered by only 0.7 kcal/mol. Since we estimate the effect of the *tert*-butyl group relative to the *n*-butyl group to be 4.5 kcal/mol, it is not unreasonable that the methyl group also has a steric effect on the rate. It is clear, however, that steric effects cannot explain all of the differences in the donor and acceptor substituents. Therefore, in order to explain the differences between the two modes of electrocyclizations, we have carried out crude model ab initio calculations on disrotatory transition structures of butadiene ring closures to compare with our previous work on the conrotatory transition structures for cyclobutene ring openings.

While the reaction studied experimentally is exothermic for ring closure ($\Delta H = -13$ kcal/mol for the conversion of *o*-xylylene to benzocyclobutene[21]), the reaction studied theoretically is exothermic for ring opening ($\Delta H = +11$ kcal/mol for the conversion of butadiene to cyclobutene[22]). This could lead to problems in interpreting substituent effects, since the transition structures for these two processes might be quite different. However, substituent effects are similar for the electrocyclic ring openings of cyclobutenes and benzocyclobutenes, even though there also large differences in the heats of reaction.[21,22] For example, the activation energy of 23.5 kcal/mol for the ring opening of 3-methoxycyclobutene is 9.4 kcal/mol[4] lower than the activation energy of the ring opening of cyclobutene (32.9 kcal/mol).[23] Likewise, the activation energy of 31.3 kcal/mol for the ring opening of α-methoxybenzocyclobutene[24] is 9 kcal/mol lower than the activation energy of the ring opening of benzocyclobutene (39.9 kcal/mol).[21] Because of the similarity of substituent effects on these two reactions, we can assume that the orbital interactions that control the conrotatory ring openings of cyclobutenes are the same as those that control the conrotatory ring openings of benzocyclobutenes.[5]

Scheme I



Computational Results

We attempted to locate an RHF transition structure for the disrotatory ring closure of butadiene to cyclobutene. However, much as we expected and like the experience of Skancke et al.,[25] the energy of the butadiene increased regularly from the starting geometry as it was distorted toward cyclobutene, since the ground state of butadiene correlates electronically with a doubly excited state of cyclobutene. Likewise, the disrotatory ring opening of cyclobutene produced a high-energy form of butadiene. We also attempted to locate a disrotatory transition structure with the UHF technique. The symmetrical stationary point that was found resembles the C_s structure of Bruelet and Schaefer[18] and has two imaginary vibrational frequencies. Thus, it is not a transition structure. It is clear that we cannot locate the disrotatory transition structure of the butadiene to cyclobutene interconversion at this level of theory.

Hsu, Buenker, and Peyerimhoff located an s-cis perpendicular allyl–methylene biradical structure as the disrotatory transition structure (Scheme I).[16] We have located a similar stationary point at the UHF/3-21G level. It is also a transition structure. This perpendicular biradical is 23.8 kcal/mol lower in energy than the second-order stationary point described above. The imaginary vibrational mode corresponds to rotation of the CH_2 group. The *s*-trans analogue of this perpendicular biradical is also a transition structure and is 0.3 kcal/mol lower in energy than the *s*-cis form. Again, the imaginary vibrational frequency corresponds to rotation of the CH_2 group of butadiene. The *s*-trans form cannot be the forbidden transition structure for the isomerization of cyclobutene and butadiene. The *s*-cis form may be, but the similarity of the two perpendicular biradicals suggests that the *s*-cis form is the transition structure for the isomerization of one double bond in butadiene. This cannot simultaneously be the forbidden transition structure, but there may be a similar structure with less symmetry that is. In spite of extensive searches, this has not been located computationally.

Unlike previous theoretical studies of the forbidden reaction, our goal was not to determine the exact nature of the disrotatory transition structure but instead to understand the substituent

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(20) Frey, H. M., Pope, B. M., Skinner, R. F. *J. Trans. Faraday Soc.* **1967**, 1166.

(21) Roth, W. R.; Biermann, M. *Chem. Ber.* **1978**, *111*, 3892. Roth, W.; Scholz, B. P. *Chem. Ber.* **1981**, *114*, 3741.

(22) Wiberg, K. B.; Fenoglio, R. A. *J. Am. Chem. Soc.* **1968**, *90*, 3395.

(23) Cooper, W.; Walters, W. D. *J. Am. Chem. Soc.* **1958**, *80*, 4220. Carr, R. W., Jr.; Walters, W. D. *J. Phys. Chem.* **1965**, *69*, 1073.

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(25) Skancke, P. N.; Yamashita, K.; Morokuma, K. *J. Am. Chem. Soc.* **1987**, *109*, 4157.

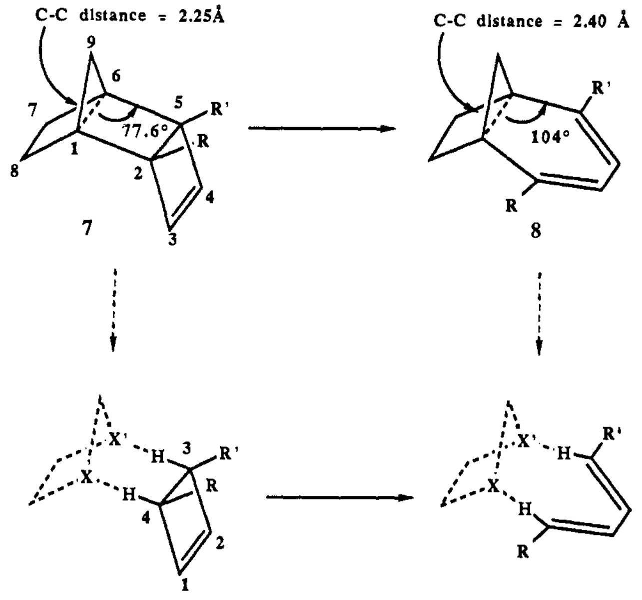
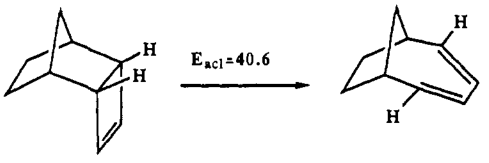


Figure 1. Constraints imposed in the calculations of disrotatory transition structures.

effects on the forbidden butadiene–cyclobutene interconversions in a geometrically constrained case. It is not feasible at present to calculate fully the interconversion of **1** and **2**, so we had to locate a system with nearly the same geometric constraints as in the interconversion of **1** and **2**. We chose to model the ring closure of **8** to **7**[26] with the use of ab initio calculations, because of the similarity to the interconversion of **1** to **2**. The computational complexity of the calculation is reduced further by removal of the cyclopentanediyl framework, which should have little effect except to force the disrotatory closure of the butadiene moiety. We studied the ring closure of the butadiene moiety by imposition of geometric constraints that force the disrotatory closure and the C–C bond-length compression in much the same way that the cyclopentanediyl framework does.



7 **8**

Figure 1 shows the geometric constraints and composite reaction coordinate used in the location of the model transition structures. C_s symmetry was maintained throughout. While the real system is not forced to be perfectly planar symmetric, it cannot stray far from this symmetry. The cyclopentanediyl framework was replaced by two dummy atoms, X and X′, placed at the MM2-optimized[27] positions of the bridgehead carbons C_1 and C_6 of compound **8**. The distance between the two dummy atoms was fixed at the C_1C_6 distance of 2.40 Å for the diene and at 2.25 Å for the cyclobutene. The X–X′ bond length was assumed to vary in a linear fashion proportional to the progress along the reaction coordinate. The C–X distance was chosen to be the same as the corresponding C_1C_2 distance found for the MM2-optimized structure of **7**. The X′–X–C angle was set to the $C_1C_6C_5$ angle of 104.0° for the diene and 77.6° for the cyclobutene. The angle was assumed to be linearly proportional to reaction progress as determined from the X–X′ distance. The synchronous change of these two variables, the X–X′ distance and the X′–X–C angle, forces a disrotatory motion. Concurrent shortening of the X–X′ distance and decreasing the X′–X–C angle both pulls C_3 and C_4 together and rotates the C_3 and C_4 methylene groups in a disrotatory fashion. The energy maximum along the pathway defined by this composite reaction coordinate was located with UHF/3-21G calculations. The model transition structures were located with the UHF method[28] and the 3-21G basis set,[29] using the GAUSSIAN 82 series of programs developed by Pople's group.[30] The use of the UHF technique permits open-shell character in the wavefunction near the orbital crossing which occurs in a forbidden reaction. The use of UHF was necessary, because the RHF search predictably yielded a surface in which the energy continued to rise as the geometry was altered from reactant to product.[25]

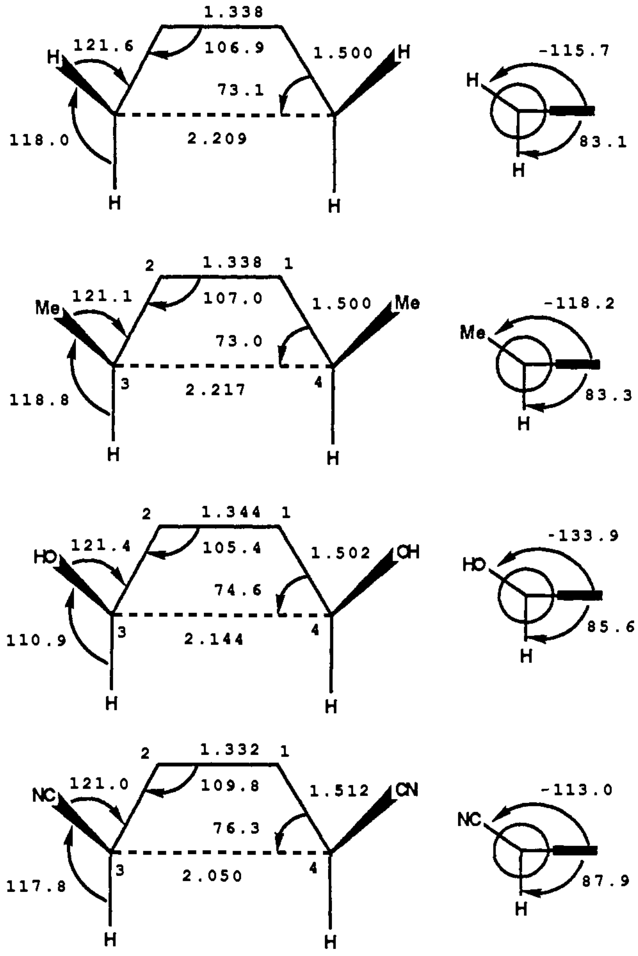


Figure 2. Geometries of the model disrotatory transition structures. Bond lengths are in Angstroms, angles and dihedral angles are in degrees.

We did not use the UHF energies to estimate activation energies, because of the large spin contamination from higher spins states and because UHF calculations overestimate the stability of diradicals relative to closed-shell energies.[25] We have chosen instead to use RHF single-point energies calculated on the UHF geometries in order to obtain a more reasonable singlet wavefunction for assessment of substituent effects. This RHF/3-21G//UHF/3-21G procedure is a rather bizarre way to do calculations. However, we cannot currently do the four-electron, four-orbital MCSCF calculation with a double-ζ basis set which might be adequate for this problem. Although our procedure is far from a final solution to the problem of calculating substituent effects on forbidden reactions, and the numbers obtained here should be considered rough guesses, the calculations stimulated the development of a qualitative theory which provides a new way

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(26) Frey, H. M.; Metcalfe, J.; Brown, J. M. *J. Chem. Soc. B* **1970**, 1586.

(27) Allinger, N. L.; Yuh, Y. *QCPE* **1980**, *12*, 395. Burkert, U.; Allinger, N. L. *Molecular Mechanics*; American Chemical Society: Washington, DC, 1982.

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(30) Binkley, J. S.; Frisch, M. J.; Krishnan, R.; DeFrees, D.; Schlegel, H. B.; Whiteside, R. A.; Fluder, E.; Seeger, R.; Pople, J. A. GAUSSIAN 82, Releases E and H, Carnegie-Mellon University, Pittsburgh, Pennsylvania.

Chart I

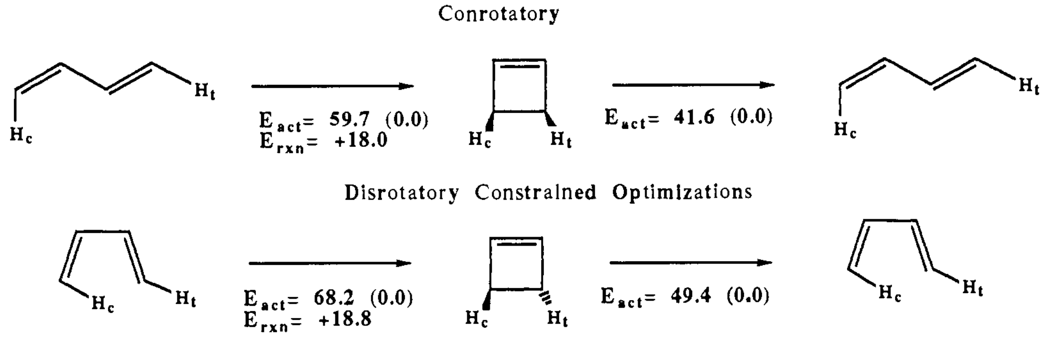
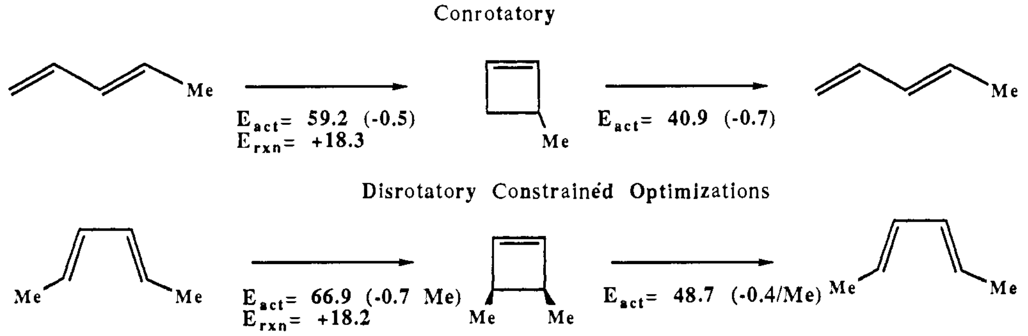


Chart II

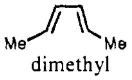
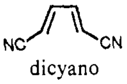


to think about substituent effects on forbidden reactions. This is the only currently available hypothesis which corresponds at all to experimental fact.

Figure 2 shows the geometries for the model disrotatory transition structures for the ring closure of *cis*-1,3-butadiene (*E*,*E*)-2,4-hexadiene, (*E*,*E*)-1,4-dihydroxy-1,3-butadiene, and (*E*,*E*)-1,4-dicyano-1,3-butadiene. Table VI summarizes the energetics of these model reactions. The methyl group is representative of weak-donor substituents such as alkyl groups, the hydroxy is a good π lone-pair donor, and the cyano group is typical of electron-withdrawing substituents. Substituted cyclobutenes and cisoid butadienes were also optimized with the above constraints. No harmonic-frequency analyses were performed, because these are stationary points only within the defined constraints.

In the model disrotatory transition structure for the cyclization of 1,3-butadiene, the C_3–C_4 bond length is 2.21 Å, which is slightly longer than the 2.14 Å of the conrotatory transition structure (see Figure 2).[4,31] Because the transition structures resemble cyclobutene more than they do butadiene, we have chosen to use the cyclobutene numbering scheme rather than the butadiene scheme in the discussions that follow. The C_1–C_2 bond length of 1.34 Å and the C_2–C_3 bond length of 1.50 Å are very similar to the cyclobutene lengths of 1.33 and 1.51 Å, respectively. The disrotatory motion involves rotation of two hydrogens toward each other (C_1–C_2–C_3–H = 83°, Figure 2), while the other hydrogens are rotated very slightly (C_1–C_2–C_3–H = 116°) and have essentially the same torsional angle that they have in cyclobutene (C_1–C_2–C_3–H = 115°). These geometric parameters indicate that the transition structure is very close to the ground state of cyclobutene. The position of the transition state is consistent with the 11.4 kcal/mol higher energy of cyclobutene, relative to *s-trans*-butadiene. The transition structure appears to be qualitatively appropriate for a forbidden process in a constrained geometry. It should be quite diradicaloid in character, involving a more or less broken σ bond with little or no overlap of the radical orbitals with the π bond. At such a geometry, mixing of nearly equienergetic configurations will allow crossing from the cyclobutene surface to the butadiene surface. The calculated activation energy for the model disrotatory transition structure for the ring closure of butadiene is 68.2 kcal/mol, while that for the disrotatory ring opening of cyclobutene is 49.4 kcal/mol. The calculated activation energy of the model disrotatory ring opening is 9 kcal/mol higher than the experimental activation energy of 40.6 kcal/mol for the disrotatory ring opening of **7**, an overestimation that is typical of activation energies of pericyclic reactions at the RHF/3-21G level (Chart I).[31]

Table VI. Calculated Energies of Constrained Cyclobutenes and Butadienes and of Models for Disrotatory Transition Structures

	 parent	 dimethyl	 dihydroxy	 dicyano
$E_{\text{cyclobutene}}$[a]	−154.022 17	−231.667 00	−302.888 98	−336.455 33
E_{ts} UHF[b]	−153.974 21	−231.619 15	−302.848 00	−336.426 46
E_{ts} RHF[c]	−153.943 39	−231.589 38	−302.825 94	−336.407 89
$E_{\text{butadiene}}$[a]	−154.052 15	−231.695 92	−302.930 18	−336.488 53
$\Delta E_{\text{reaction}}$[d]	18.8	18.2	25.9	20.8
E_{act} ring closure[e]	68.2	66.9	65.4	50.6
$\Delta E^{\ddagger}_{\text{rel}}$ ring closure[f]	0	−1.3	−2.8	−17.6
E_{act} ring opening[g]	49.4	48.7	39.6	29.8
$\Delta E^{\ddagger}_{\text{rel}}$ ring opening[h]	0	−0.7	−9.8	−19.6

[a] RHF energy in hartrees. [b] Optimized UHF/3-21G energies in hartrees. [c] RHF/3-21G//UHF/3-21G energy in hartrees. [d] Energy of reaction, in kilocalories/mole, calculated at the RHF/3-21G level, for conversion of the butadiene to the corresponding cyclobutene. [e] Estimated activation energy, in kilocalories/mole, of the ring-closure reaction calculated at the RHF/3-21G//UHF/3-21G level. [f] Activation energy of the ring-closure process relative to the parent reaction. [g] Estimated activation energy, in kilocalories/mole, of the ring-opening reaction calculated at the RHF/3-21G//UHF/3-21G level. [h] Activation energy of the ring-opening process relative to the parent reaction.

Methyl groups have very little effect on either the geometry or on the activation energy of the model disrotatory transition structure, as can be seen for the transition structure for the ring closure of (*E*,*E*)-2,4-hexadiene to form *cis*-3,4-dimethylcyclobutene (Chart II). The C_3C_4 bond length of 2.22 Å is virtually unchanged from that in the parent transition structure, as are the remaining C–C bond lengths. The rotations of the termini are

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(31) Spellmeyer, D. C.; Houk, K. N. *J. Am. Chem. Soc.* **1988**, *110*, 3412.

Chart III

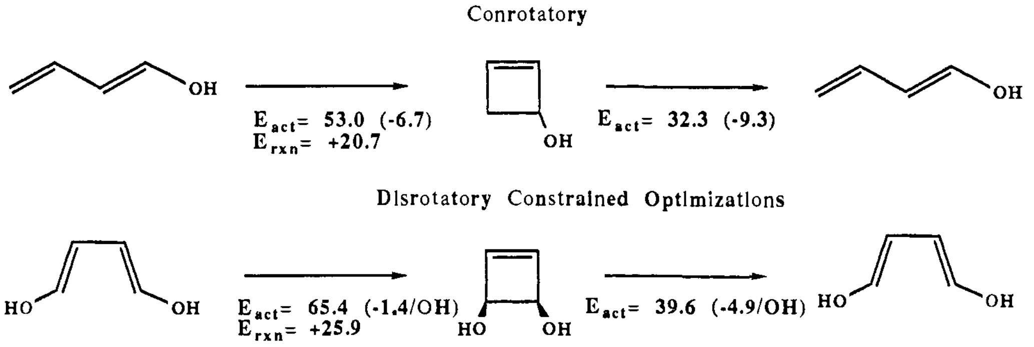
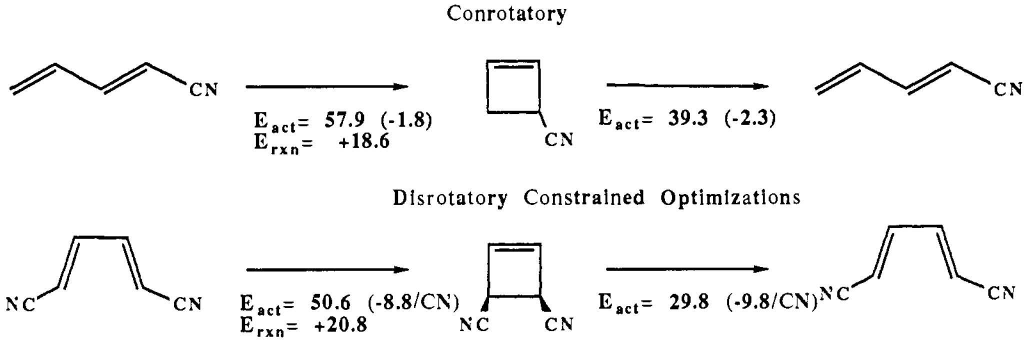


Chart IV



2° less (C_1–C_2–C_3–Me = 118°) than in the parent transition structure (C_1–C_2–C_3–H = 116°), perhaps due to the steric congestion of the two methyl groups being brought together. The calculated activation energy is 66.9 kcal/mol for ring closure of 2,4-hexadiene and 48.7 kcal/mol for the ring opening of the dimethylcyclobutene. The calculated substituent effect of the ring closure of 0.7 kcal/mol per methyl is quite different from the experimental value of 3.7 kcal/mol. However, as mentioned before, this large substituent effect is likely due to the relief of steric congestion of the *tert*-butyl and the methyl groups with the hydrogens at the bridgehead carbons. The calculated substituent effects for both disrotatory and conrotatory ring closure reactions are comparable.[4,5]

In order to probe whether steric effects cause the 3 kcal/mol difference between the ab initio and the experimental values, we optimized the structures of **1c**, **1f**, **2c**, and **2f** with the modified Allinger method contained in Still's MODEL program.[32] The difference in steric energy of the structures **1c** and **2c** is 39.3 kcal/mol, while the difference in energy between **1f** and **2f** is 34.1 kcal/mol. The larger difference in the energy between **1c** and **2c** relative to **1f** and **2f** is a result of the increased steric repulsion present in **1f** caused by the methyl group and the hydrogen at the bridgehead of the norbornyl moiety and with the hydrogen on the *o*-xylylene fragment. Thus, the observed substituent effect for the ring closure of **1f** relative to that of **1c** is predominantly steric in origin. It is likely that the influence of trimethylsilyl is also steric in origin, although we have no calculation to support this conjecture.

Hydroxyl substituents have a more pronounced effect on the disrotatory transition structure, as found in the ring closure of (*E*,*E*)-1,4-dihydroxy-1,3-butadiene (Chart III). The C_3–C_4 bond length of 2.14 Å is slightly shorter than that of the parent system. The C_1C_2 and C_1C_4 bond lengths have changed less than 0.01 Å from those of the unsubstituted transition structure. The hydroxyl groups have rotated from the butadiene positions some 15° less (C_1–C_2–C_3–O = 134°, Figure 2) than the methyl groups in the ring closure of 2,4-hexadiene and 18° less than the corresponding hydrogens in the ring opening of cyclobutene. The activation energy for the disrotatory ring closure of 1,4-dihydroxy-1,3-butadiene is 65.4 kcal/mol, which is only 2.8 kcal/mol lower than the activation energy for the ring closure of butadiene. This is because the diene is stabilized appreciably by conjugation with the hydroxy groups. The calculated substituent effect of 1.4 kcal/mol per hydroxyl group for the activation energy for the disrotatory ring closure is about one-half of the experimental value of 3.2 kcal/mol found for that of OMe group, **1e**, and is considerably lower than the value of 6.2 kcal/mol calculated for the conrotatory ring closure of (*E*)-1-hydroxybutadiene.

Cyano groups have a much larger effect on the transition structure and on the activation energy for ring closure than do the other groups studied. The model transition structure for the reaction of (*E*,*E*)-1,4-dicyano-1,3-butadiene is shown in Figure 2. The C_3C_4 bond length of 2.05 Å is 0.15 Å shorter than that in the parent transition structure. The C_1C_2 bond is shorter and the C_1C_4 bond is longer than in the parent transition structure. The degree of rotation of the CN groups (C_1–C_2–C_3–CN = 113°) is 3° more toward the cyclobutene structure than in the parent transition structure. The calculated activation energy for the ring closure is 50.6 kcal/mol, and that of the ring opening is 29.8 kcal/mol (Chart IV). Thus, each cyano group lowers the activation energy of the disrotatory ring closure by 8.8 kcal/mol and lowers the activation energy of the ring opening by 9.8 kcal/mol. However, a cyano group is calculated to lower the activation energy of the conrotatory ring closure by only 1.8 kcal/mol, which shows that the substituent effect on the disrotatory ring opening is about four times as large as on the conrotatory ring opening. The 8.8 kcal/mol lowering of the activation energy of the ring closure reaction compares quite favorably with the experimentally determined 8.7 kcal/mol lowering of the activation energy for the CO_2Me group of **1h**.

In contrast to Carpenter's Hückel based theory,[2] electron-donating groups have a much different effect on the disrotatory transition state for ring closure of substituted butadienes than do electron-withdrawing groups. Both OH and Me groups lower the activation energy of the transition structure for ring closure by about one-half to one-fourth as much as they do for the conrotatory process. A CN group, however, lowers the activation energy of the disrotatory ring closure by 9 kcal/mol, an amount which is four times as large as in the conrotatory transition state for ring closure. The same trends are found for the ring-opening reaction. Donors have a small effect on the disrotatory ring opening, but acceptors have a large effect.

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(32) Still, W. C. MODEL, version 1.3, Columbia University, New York.

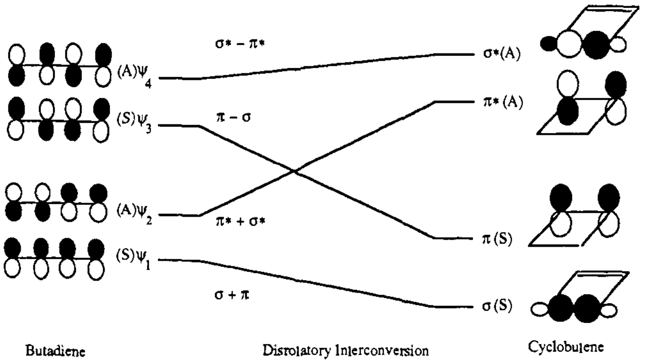

Figure 3. Woodward–Hoffmann orbital-correlation diagram for the disrotatory interconversion of butadiene and cyclobutene.

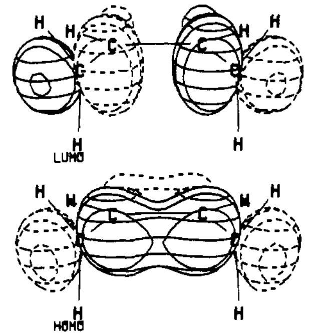

Figure 4. Jorgensen plots of the HOMO and LUMO of the model disrotatory transition structure for the disrotatory interconversion of cyclobutene and butadiene.

Since there is considerable diradical character at the transition structure, the substituent effects on the disrotatory reaction might be expected to parallel the radical-stabilization energies. This is not the case, however. Pasto et al. have determined the stabilization energies for several substituents with ab initio methods. These compare well with experimental data, when available.[33] A methyl group stabilizes a radical by 3.3 kcal/mol, a hydroxy group does so by 5.7 kcal/mol, and a cyano group does so by 5.3 kcal/mol. The predicted effect of substituents would then be Me $<$ OH $\approx$ CN, on the basis of these radical stabilization energies. Our calculations indicate that the substituent effects follow the order OH $\approx$ Me $\ll$ CN. Thus, radical-stabilization energies alone cannot explain the substituent effects on the disrotatory reaction or on the conrotatory reactions.

We have devised a hypothesis which explains these unusual substituent effects. While it is based on relatively limited data, it does provide many predictions for future experimental and computational tests. Figure 3 shows the Woodward–Hoffmann correlation diagram for this forbidden reaction.[34] The correlation diagram shows occupied ground-state orbitals of a reactant correlating with vacant orbitals of product. The transition state will be in the general vicinity of the HOMO–LUMO crossing, where the proper description of the transition state is in terms of a multiconfigurational wavefunction.

Figure 4 shows Jorgensen plots[35] of the STO-3G HOMO and LUMO of the model constrained disrotatory transition structure of the ring closure of butadiene. The HOMO of the cyclobutene-like model transition state is composed of the breaking σ_{C-C} orbital, mixed to a small extent in an antibonding fashion with the π orbital of the alkene. It is related to ψ_3 of butadiene and may best be described as $\sigma-\pi$. A high energy HOMO occurs in the transition state because of the strong mixing of the σ_{C-C} and π MO's upon disrotatory motion. The LUMO is the σ^* orbital mixed only slightly, in a bonding fashion, with the π^* orbital. It is $\sigma^*-\pi^*$ and is a highly distorted version of ψ_2 of butadiene.

As described later, the relatively high energies of both the HOMO and LUMO are important in explaining the observed substituent effects.

A modified Woodward–Hoffmann orbital-correlation diagram is shown in Figure 5. Starting at the right side of Figure 5, if the C–C bond of cyclobutene is stretched without rotation, the σ orbital rises dramatically in energy, and the σ^* orbital drops. These orbitals cannot mix with the π and π^* orbitals until appreciable rotation of the termini occurs. If we start from the butadiene orbitals at the left side of the figure, rotation without bringing the termini near bonding distance gives the same pattern, with a stretched σ orbital as the HOMO (derived from mixing of ψ_1 and ψ_3) and a stretched σ^* orbital as the LUMO (derived from mixing of (ψ_2 and ψ_4). The calculations imply that the transition structure has a HOMO that is primarily a σ_{C-C} orbital and a LUMO that is primarily a $\sigma^*{}_{C-C}$ orbital.

As was shown earlier for the conrotatory reaction,[4] the HOMO and LUMO of the disrotatory transition structure are primarily σ and σ^* orbitals, distorted and moved closer in energy by the decrease in overlap between the orbitals on carbons 3 and 4, relative to the cyclobutene orbitals. The degree of rotation allows the component atomic orbitals of the σ_{C-C} and $\sigma^*{}_{C-C}$ orbitals to maintain a larger amount of overlap in the disrotatory transition structure than in the conrotatory transition structure, where the twist of the carbon skeleton distorts the σ_{C-C} and $\sigma^*{}_{C-C}$ orbitals. That this is the case can be seen in Figure 6. Here we present the results of model transition structure calculations for the conrotatory and the disrotatory ring openings of cyclobutane and cyclobutene. In these calculations, we have rotated the terminal CH_2 groups to the same extent in both the conrotatory and disrotatory modes, while keeping the carbon skeleton planar. The energy of the σ_{C-C} orbital in cyclobutane rises rapidly to −7.2 eV from −11.1 eV as the C–C bond is stretched and as 15° of conrotation is enforced. At the same time, the $\sigma^*{}_{C-C}$ orbital decreases to 6.6 eV from 16.5 eV in planar cyclobutane. When a disrotatory motion of 15° is enforced, the σ_{C-C} orbital energy increases to −7.5 eV and the $\sigma^*{}_{C-C}$ orbital decreases in energy to 6.8 eV. Thus, there is a larger effect on the energies of the σ_{C-C} and $\sigma^*{}_{C-C}$ orbitals in the conrotatory opening than in the disrotatory. This is due to the fact that the conrotatory motion twists the constituent orbitals at C_3 and C_4 apart, decreasing the overlap of orbitals at C_3 and C_4 more than in the disrotatory reaction. The orbitals at C_3 and C_4 in the disrotatory ring opening maintain greater overlap, and thus, the σ_{C-C} orbital is lower in energy and the $\sigma^*{}_{C-C}$ orbital is higher in energy than in the conrotatory ring opening. In cyclobutene, however, these orbitals mix with the orbitals of the π system. Figure 6 also shows the energies of the σ_{C-C} and $\sigma^*{}_{C-C}$ orbitals in a model transition structure for the ring opening of cyclobutene. In these calculations, the carbon framework is held planar. For the transition state models, the hydrogens on C_3 and C_4 have been conrotated or disrotated 15°, and the C_3–C_4 distance has been increased to 2.10 Å. The higher lying σ_{C-C} orbital of the conrotatory transition structure mixes with the π^* orbital, resulting in a net stabilization of the σ_{C-C} orbital (−7.9 eV). The $\sigma^*{}_{C-C}$ orbital mixes with the π orbital, lowering the energy of the π and raising the energy of the $\sigma^*{}_{C-C}$ orbital slightly, relative to the conrotatory ring opening of cyclobutane. Because these orbitals are relatively far apart energetically, the overall effect on the orbital energies is small. This is not the case in the disrotatory system, however. In this case, the σ_{C-C} orbital mixes with the π orbital, which raises the energy of the HOMO (−7.3 eV), relative to the ring opening of cyclobutane. The $\sigma^*{}_{C-C}$ orbital, however, mixes with the π^* orbital in a bonding fashion, producing a LUMO that is nearly the same energy as the LUMO of the conrotatory reaction.

Carpenter's model, by virtue of the fact that it relies on a Hückel approximation, predicts in effect that the HOMO of the conrotatory ring opening would be raised to the same extent as the LUMO is lowered. His model, like ours, would predict that the HOMO of the disrotatory transition structure is higher than the

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[33] Pasto, D. J.; Krasnansky, R.; Zercher, C. *J. Org. Chem.* **1987**, *52*, 3062.

[34] Woodward, R. B.; Hoffmann, R. *The Conservation of Orbital Symmetry*; Verlag Chemie International: Deerfield Beach, FL, 1970.

[35] We thank Dr. W. L. Jorgensen for a Harris version of his program.

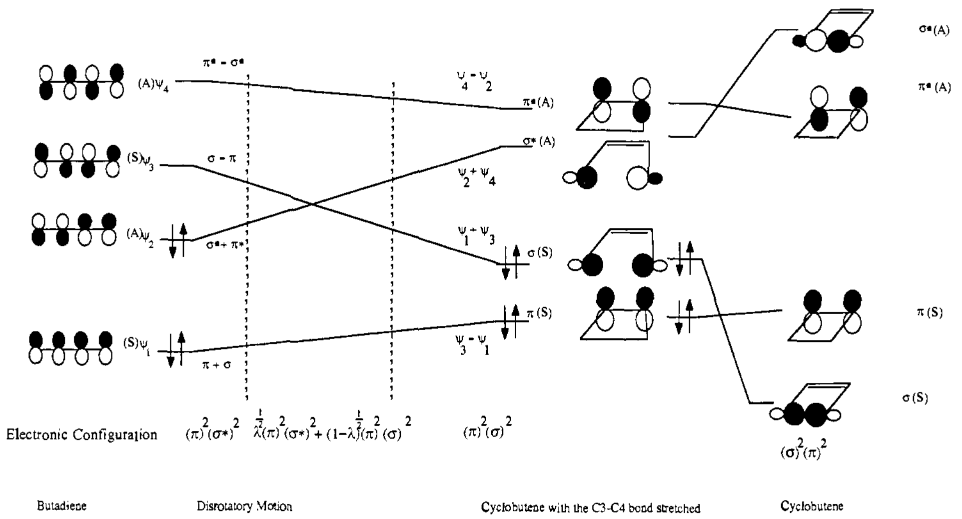

Figure 5. Orbital correlation diagram for the nearly stepwise interconversion of butadiene to cyclobutene. The disrotatory process is assumed to involve first the disrotatory rotation of the butadiene termini, which produces the orbitals in the center, followed by compression of the C–C bond, which produces the orbitals on the right.

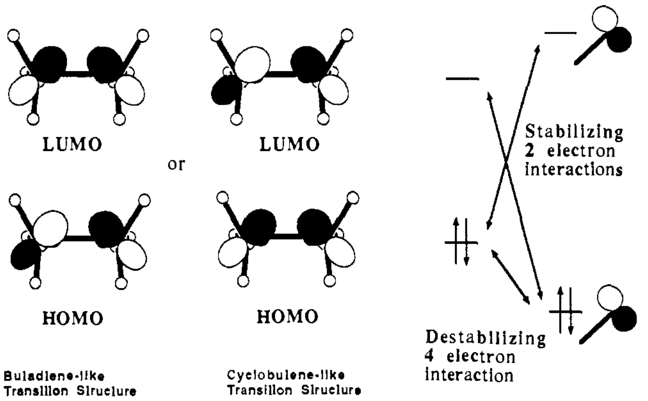

Figure 6. Representation of the orbital interactions of the HOMO and LUMO of the disrotatory transition structure with a filled p orbital or vacant p orbital of a substituent.

HOMO of the conrotatory, since the disrotatory reaction proceeds via an antiaromatic transition state. Unlike our model, Carpenter's model also predicts that the LUMO of the disrotatory transition state will be lower than that of the conrotatory.

The effects on the disrotatory transition structure of substituents at C_3 and C_4 of cyclobutene arise primarily from interactions of substituent orbitals with the breaking σ and σ^* orbitals, much as in the conrotatory transition structure.[4,5] Thus, in Carpenter's model, donors (which alter the energy of the LUMO) are predicted to have the same effect on the activation energy of the system as acceptors (which alter the energy of the HOMO). Our model, on the other hand, predicts that acceptors will have a much larger effect on the transition state than donors. It is the unusually high-energy HOMO and high-energy LUMO of the disrotatory transition structure, relative to the conrotatory transition structure, that give rise to the enhanced effect of acceptors and the diminished effect of donors on the forbidden reaction relative to the allowed reaction.

We have assumed in this discussion that the HOMO of the disrotatory transition structure is largely composed of the σ_{C-C} orbital and that the LUMO is composed primarily of the σ^*_{C-C} orbital. This representation is accurate on the cyclobutene side of the reaction coordinate. If the transition structure occurs before the degeneracy of the HOMO and LUMO, the HOMO of the transition structure is predominantly the σ^*_{C-C} orbital and the LUMO is predominantly the σ_{C-C} orbital. The RHF calculations bias the HOMO to be primarily the σ_{C-C} orbital and the electronic configuration of the transition structure to be $(\pi)^2(\sigma)^2(\sigma^*)^0$. The true electronic configuration near the transition structure is best represented as some combination of the $(\pi)^2(\sigma)^2(\sigma^*)^0$ configuration and the $(\pi)^2(\sigma)^0(\sigma^*)^2$ configuration (see Figure 5). That is, the electronic configuration is represented by the equation $\lambda^{1/2}(\pi)^2(\sigma)^2(\sigma^*)^0 + (1 - \lambda)^{1/2}(\pi)^2(\sigma)^0(\sigma^*)^2$, where $0 \leq \lambda \leq 1$, and the HOMO is some combination of σ_{C-C} and σ^*_{C-C} orbitals, with some π and π^* mixed in.

The overlap of an outwardly rotating substituent orbital with the HOMO and LUMO is primarily confined to the orbitals on the adjacent carbon. That is, a substituent on C_3 has a large interaction with the atomic orbital on C_3, but not with the atomic orbital on C_4. This would be different if the substituents rotate inward, but in the system under study, the ring carbons rotate inward and substituent groups outward. Since the interaction occurs mainly with the adjacent atomic orbital, the same substituent effect occurs no matter whether σ or σ^* is the HOMO.

The transition structure of the *o*-xylylene ring closure is likely to be more butadiene-like than the transition structure of the butadiene ring closure. Consequently, the HOMO may have more σ^*_{C-C} character and the LUMO more σ_{C-C} character. However, the substituent will interact both with the filled and vacant σ and the filled and vacant σ^* orbital, due to the multiconfigurational nature of the ground state.

Figure 7 shows the HOMO and LUMO of the transition structure along with p orbitals, representing the occupied p (or π) and the vacant p (or π) orbitals of a substituent. The interaction of the high-lying donor orbital of the substituent, such as a lone pair on oxygen, with the LUMO, which can be either the σ_{C-C} or the σ^*_{C-C} orbital, is a stabilizing two-electron interaction that raises the energy of the LUMO and lowers the energy of the substituent orbital. The donor orbital also mixes with the HOMO in a four-electron destabilizing interaction, which also lowers the energy of the substituent orbital but raises the energy of the HOMO. The two-electron interaction leads to a large energy change, so the transition structure is stabilized. The same type of interactions are found for donor substituent effects on the conrotatory reaction. Indeed, the influence of outwardly rotating donors is similar for conrotatory and disrotatory reactions.

The interactions of the donor orbital with the HOMO and LUMO should serve to raise the energy of both the HOMO and LUMO, in the absence of any geometric perturbations. This is seen for the 2,4-hexadiene transition structure. The HOMO and LUMO are raised by 0.61 and 0.26 eV, respectively, relative to the disrotatory transition structure for the ring closure of butadiene. The transition structure for the ring closure of 1,4-dihydroxy-1,3-butadiene to form *cis*-3,4-dihydroxycyclobutene, however, is more diene-like than the corresponding transition structure for the ring closure of butadiene. In the absence of a donor orbital, this geometric perturbation produces a lower energy LUMO and a higher energy HOMO than in the parent transition structure. Furthermore, the electronegative oxygen will inductively

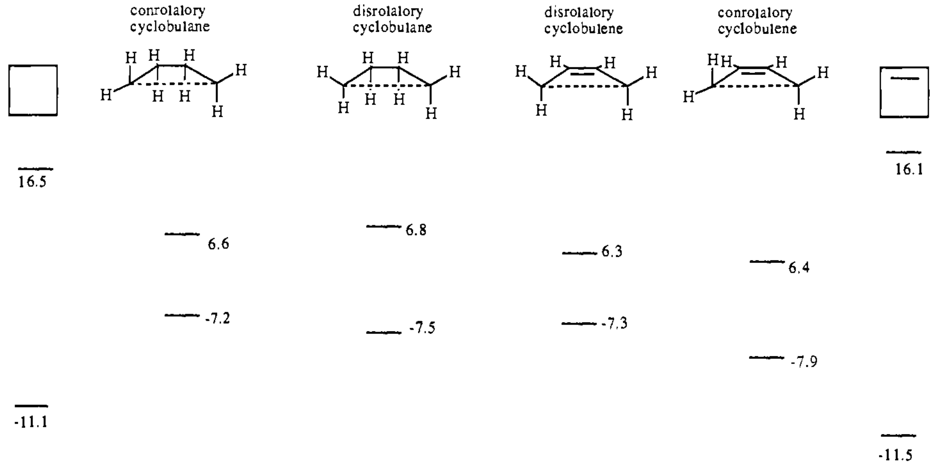

Figure 7. STO-3G orbital energies of the σ and σ^* orbitals in model conrotatory and disrotatory ring openings of cyclobutane and cyclobutene. Energies are in eV.

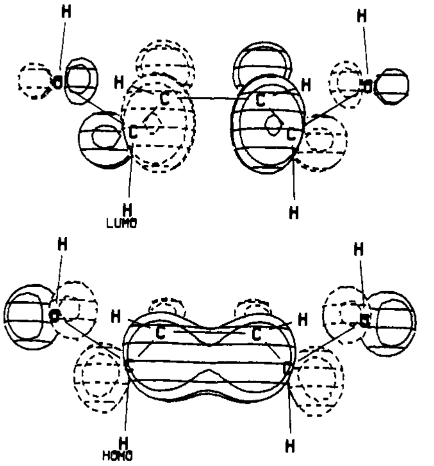

Figure 8. HOMO and LUMO of the 1,4-dihydroxybutadiene model disrotatory transition structure.

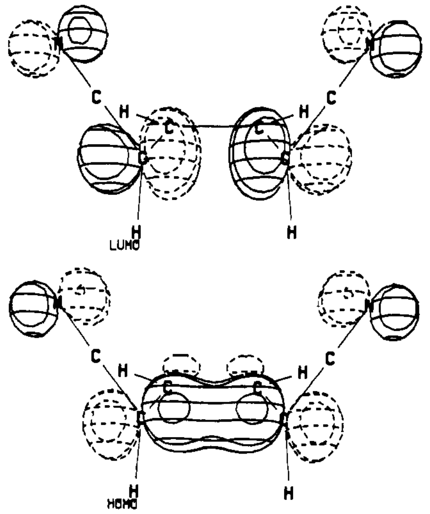

Figure 9. HOMO and LUMO of the 1,4-dicyano-1,3-butadiene model disrotatory transition structure.

lower the energies of both the HOMO and the LUMO. The donor orbitals mix with the displaced HOMO and LUMO as described above, resulting in a HOMO that is 0.35 eV higher than in the unsubstituted reaction and a LUMO that is 0.20 eV lower in energy than in the unsubstituted transition structure. Figure 8 shows the HOMO and LUMO for the dihydroxy model transition structure, as estimated at the RHF/STO-3G//UHF/3-21G level.

Electron-acceptor substituents have low-lying vacant orbitals. They will mix with the HOMO in a bonding fashion, resulting in an overall stabilization of the transition structure. The vacant π^*_{CN} orbitals mix with the HOMO in a stabilizing two-electron interaction. However, in addition to having low-lying vacant orbitals, the cyano group has filled π orbitals, one of which mixes with the HOMO in a destabilizing four-electron interaction. This high-lying π_{CN} orbital also mixes in a stabilizing two-electron interaction with the LUMO. The overall result is an overwhelming stabilization of the disrotatory transition structure by the cyano groups. The HOMO and LUMO of the transition structure for ring closure of 1,4-dicyano-1,3-butadiene is shown in Figure 9. This large lowering of the activation energy is not seen in the conrotatory transition structure, because the HOMO of the conrotatory transition structure is relatively low-lying, diminishing the π^*_{CN}–HOMO interaction. In the disrotatory transition structure, the HOMO is higher lying, which allows the π^*_{CN}–HOMO stabilizing interaction to be very large, producing a large stabilization of the disrotatory transition structure.

The large difference in the substituent effect of the cyano group in the disrotatory transition structure relative to the conrotatory transition structure suggests that the disrotatory pathway might compete with the conrotatory pathway in the ring opening of *cis*-3,4-dicyanocyclobutene. Each cyano group stabilizes the disrotatory structure by 10 kcal/mol, which would amount to a 20 kcal/mol stabilization for the disrotatory ring opening of *cis*-3,4-dicyanocyclobutene. An outward-rotating CN group stabilizes the conrotatory transition structure by 2.3 kcal/mol, which would be offset by the 2.3 kcal/mol by which inward rotation of a CN group destabilizes the conrotatory process.[6] The activation energy of the disrotatory transition state for the ring opening of cyclobutene is predicted to be about 15 kcal/mol above the conrotatory transition state for the ring opening of cyclobutene.[36] If all of these quantities are additive, the disrotatory transition state should be approximately 5 kcal/mol lower than the conrotatory one for *cis*-3,4-dicyanocyclobutene!

In order to test this qualitative, if numerical, prediction, full geometry optimizations of the ground-state structures and the conrotatory and disrotatory transition structures of cyclobutene and of *cis*-3,4-dicyanocyclobutene have been performed. The disrotatory transition structure was located at the UHF/3-21G level constrained to C_s symmetry, but without the remaining constraints described earlier. RHF single point calculations on the UHF geometries provide estimates of the activation energies. The conrotatory transition structure was located at the RHF/3-21G level.

The conrotatory transition structure for the ring opening of cyclobutene has been described previously.[4,31] The activation

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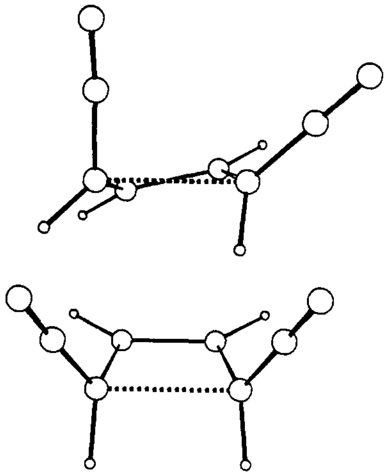

Figure 10. Conrotatory and disrotatory transition structures of the *cis*-3,4-dicyanocyclobutene ring opening.

energy is 41.6 kcal/mol at the 3-21G level. The experimental activation energy is 32.9 kcal/mol.[23] Not surprisingly, the disrotatory transition structure as calculated at the UHF/3-21G level is found to have two imaginary vibrational frequencies. The larger corresponds to cleavage of the C_3–C_4 bond, while the smaller corresponds to a conrotatory motion. This implies that, even at the UHF level, the conrotatory transition structure is the only mode of ring opening of cyclobutene to butadiene, although a transition structure of lower symmetry might exist.

The two transition structures for the *cis*-3,4-dicyanocyclobutene ring opening are shown in Figure 10. The RHF activation energy for the conrotatory process is 40.9 kcal/mol, a net stabilization of 0.7 kcal/mol, which is in agreement with the predicted substituent effect of nearly zero described above. The harmonic-frequency analysis shows only one imaginary vibrational frequency corresponding to conrotatory motion. The *RHF* single-point energy on the UHF geometry of the disrotatory transition structure gives an activation energy of 32.6 kcal/mol, which is 8.3 kcal/mol *lower* than for the conrotatory reaction! The harmonic-frequency analysis, calculated at the UHF level, gives only one imaginary vibrational frequency for this transition structure corresponding to the disrotatory motion. Therefore, the ring opening of *cis*-3,4-dicyanocyclobutene is a likely candidate to undergo ring opening through a disrotatory pathway.

In spite of this exciting prediction that the ring opening will follow the nominally forbidden disrotatory mode, it is far too approximate a result for a definite prediction to be made. Furthermore, a study by Mündnich and co-workers has shown that dimethyl 1,2-diphenylcyclobutene-*cis*-3,4-dicarboxylate opens exclusively through the conrotatory process,[37] indicating that despite the expected large stabilization of the disrotatory transition structure by the electron-withdrawing ester groups, the conrotatory mode is still lower in energy. Nevertheless, the cyano compound remains an intriguing one for study, and the diformyl compound might be an even better candidate.[6]

Conclusion

The activation energies for the disrotatory electrocyclizations of several bridged *o*-xylylenes have been measured. Theoretical calculations on model transition structures have shown that the unusually large stabilization of the disrotatory transition structure by electron-acceptor groups is due to the stabilization of the high-lying HOMO by the vacant substituent orbitals. Donors, on the other hand, have a smaller effect on the activation energy. Carpenter's prediction that substituents at C_3 and C_4 should show a larger substituent effect on the forbidden reaction than on the allowed reaction is shown to be correct in the case of electron-acceptor substituents, but just the opposite is found for electron-donors.

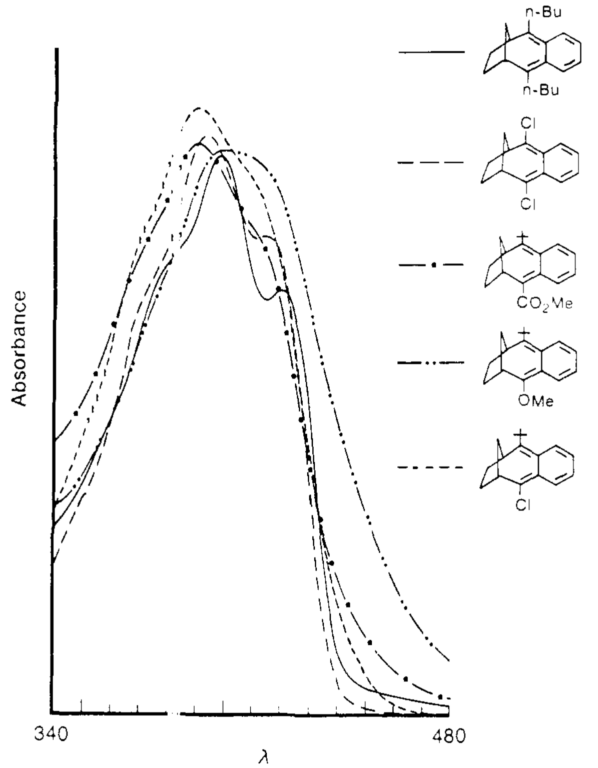

Figure 11. Absorption spectra of several bridged *o*-xylylene derivatives.

Experimental Section

^1H NMR spectra were recorded on a Varian EM-390 spectrometer using tetramethylsilane as an internal standard. ^{13}C NMR spectra were run on a Varian CFT-20 machine. Infrared spectra were taken on a Perkin-Elmer 297 instrument. The UV spectra were recorded on either a Hewlett Packard 8450A or a Varian Cary 17 machine. All of the compounds described in this study were prepared and characterized as described previously.[19] Research-grade 3-methylpentane (Phillips) was the solvent for all of the irradiations and kinetic runs. It was used as obtained without further purification.

Irradiations and Kinetic Studies. Samples of the respective benzocyclobutene derivatives **2a**–h were dissolved in 3-methylpentane ($\approx 3 \times 10^{-4}$ M), and placed in 1-cm quartz cuvettes which were thoroughly freeze thaw degassed ($< 10^{-4}$ mm) and sealed. The cuvettes were treated with 10% hexamethyldisilazane in toluene and dried at 120 °C before use. The tubes were cooled to 77 K in a quartz Dewar and irradiated using a Cermax 150-W Xenon lamp and a 254-nm solution band-pass filter (40% transmittance at 254 nm).[38] Irradiation times varied from 15 to 45 min. The presence of the bridged *o*-xylylene derivatives was signified by the appearance of a yellow color in the matrix produced by an absorption band centered around 400 nm.[39] The absorption spectra of the bridged *o*-xylylene derivatives **1** in the visible region were all remarkably similar, as shown in Figure 11. The irradiation was continued until the absorbance at the long-wavelength maximum reached 1.5–1.8. At this point, the sample was removed from the liquid nitrogen, warmed to −78 °C, and vigorously shaken to insure a homogeneous solution. The tube was then immersed in a thermostated bath and the rate of conversion of the *o*-xylyene derivative was monitored by the disappearance of the long-wavelength absorption. The measurements were continued for at least 4 half-lives. In each case, the complete disappearance of the band around 400 nm was accompanied by the reappearance of the structured band around 250–280 nm characteristic of the starting materials. Subsequent UV and GLPC analysis of the samples revealed the presence of no additional products. The activation energies were determined by Arrhenius plots at a least five temperatures per sample. The rate constants and activation energies were determined by a least-squares analysis of the data. The activation energies thus obtained for the ring closure of **1a**–h to **2a**–h are shown in Table IV.

Acknowledgment. We are grateful to the National Science Foundation for partial financial support of this research.

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Registry No. **1a**, 120685-79-2; **1b**, 120685-80-5; **1c**, 120685-81-6; **1d**, 120685-82-7; **1e**, 120685-83-8; **1f**, 120685-84-9; **1g**, 120685-85-0; **1h**, 120685-86-1; **2a**, 96430-12-5; **2b**, 120786-15-4; **2c**, 96430-06-7; **2d**, 96430-10-3; **2e**, 96430-14-7; **2f**, 96430-07-8; **2g**, 96430-08-9; **2h**, 96430-11-4; **7**, 29846-24-0; **8**, 6572-82-3; $H_2C{=}CHCH{=}CH_2$, 106-99-0; (*E*)-$H_2C{=}CHCH{=}CHCH_3$, 2004-70-8; (*E*)-$H_2C{=}CHCH{=}CHOH$, 70411-98-2; (*E*)-$H_2C{=}CHCH{=}CHCN$, 2180-68-9; (*E*)-$H_2C{=}CHCH{=}CHCHO$, 20432-40-0; (*E*,*E*)-$H_3CCH{=}CHCH{=}CHCH_3$, 5194-51-4; (*E*,*E*)-$HOCH{=}CHCH{=}CHOH$, 120685-87-2; (*E*,*E*)-$NCCH{=}CHCH{=}CHCN$, 5867-88-9; cyclobutene, 822-35-5; 3-methylcyclobutene, 1120-55-4; 3-hydroxycyclobutene, 113747-67-4; 3-cyanocyclobutene, 109364-40-1; 3-formylcyclobutene, 109364-41-2; *cis*-3,4-dimethylcyclobutene, 1517-14-2; *cis*-3,4-dihydroxycyclobutene, 60090-87-1; *cis*-3,4-dicyanocyclobutene, 120685-88-3.

Chiral Induction in Photochemical Reactions. 10.[1] The Principle of Isoinversion: A Model of Stereoselection Developed from the Diastereoselectivity of the Paternò–Büchi Reaction

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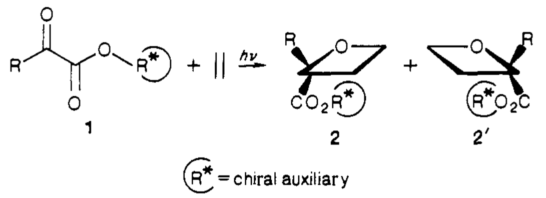
Contribution from the Institut für Organische Chemie der RWTH Aachen Prof.-Pirlet-Strasse 1, D-5100 Aachen, Federal Republic of Germany. *Received July 25, 1988. Revised Manuscript Received February 1, 1989*

Abstract: In the Paternò–Büchi reaction of the chiral phenylglyoxalates **a–c** with cyclic olefins **3–6**, the diastereomeric oxetanes **3–6a–c** and **3–6a′–c′** are formed *endo*-phenyl selectively in high chemical yields. The temperature dependence of the diastereoselectivity yields two linear functions in the corresponding Eyring diagrams. Two sets of activation parameters ($\Delta\Delta H^{\ddagger}_1$ and $\Delta\Delta S^{\ddagger}_1$, and $\Delta\Delta H^{\ddagger}_2$ and $\Delta\Delta S^{\ddagger}_2$) are derived from each Eyring diagram. There exists a linear correlation between the new parameters $\delta\Delta\Delta H^{\ddagger}$ and $\delta\Delta\Delta S^{\ddagger}$, which we call the principle of isoinversion. Furthermore isoselective relationships were observed in the Eyring plots with regard to the change of the chiral auxiliary and the change of olefins. These isoselective relationships as well as the principle of isoinversion allow a mechanistic description of the diastereoselection in the Paternò–Büchi reaction with cyclic olefins.

The Paternò–Büchi reaction[2] is one of the best known photoreactions[3,4] not only because of its preparative interest (e.g. "photoaldolization")[5] but also as a very useful example for studying the selection processes in bimolecular photochemical reactions. The addition of $^3(n\pi)^*$-excited chiral α-keto esters (type **1**) to electron-rich olefins leads in high chemical yields to the diastereomeric oxetanes **2** and **2′** shown in reaction 1.[6,7]

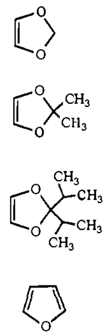
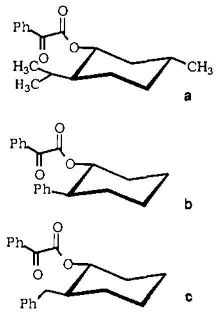
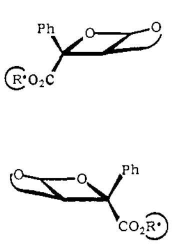


(1)

During our systematic investigation of the chiral induction observable in this reaction,[7,8] we found that the following items determine the degree of stereoselection: the structure of the chiral auxiliary R*–OH,[7,8,9] the nature of the substituent R in the α-keto moiety,[7,10] the olefinic partner, and the reaction conditions (solvent,[11] addition of metal ions,[11] and in particular the reaction temperature[7b,8]).

Neither the irradiation time nor the concentration of the reactants have any significant influence on the product distribution. Hitherto temperature dependences of diastereoselective photochemical processes have been investigated only in a few cases.[12] Primarily we observed the dependence of temperature in diastereo- and regioselection[13] processes in the systems of tetramethylethylene and 1,1′-diethoxyethylene and chiral α-keto esters,[7,8] respectively.

Table I. Structures[7,8] of the Applied Cyclic Olefins **3–6** and Chiral Phenylglyoxalates **a–c**[a]

cyclic olefin	chiral phenylglyoxalate	excess and minor oxetane
 **3** **4** **5** **6**	 **a** **b** **c**	 **3a - c** **4a - c** **5a - c** **6a - c** **3a′ - c′** **4a′ - c′** **5a′ - c′** **6a′ - c′**

[a] The numbering of the oxetane is composed of the olefin number and the letter of the phenylglyoxalate. The minor isomer is indicated with a prime. The phenylglyoxalates **b** and **c** were used in racemic form. There are no different results by using the enantiomerically pure phenylglyoxalates.

The ln *P* values were found to be linearly dependent on the reciprocal of temperature according to the Eyring formalism:[14]

$$\ln P = \frac{-\Delta\Delta H^{\ddagger}}{R}\frac{1}{T} + \frac{\Delta\Delta S^{\ddagger}}{R} \qquad (2)$$

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† Dedicated to the memory of David Ginsburg.

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0002-7863/89/1511-5367$01.50/0