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Origins of Inward Torquoselectivity by Silyl Groups and Other σ-Acceptors in Electrocyclic Reactions of Cyclobutenes

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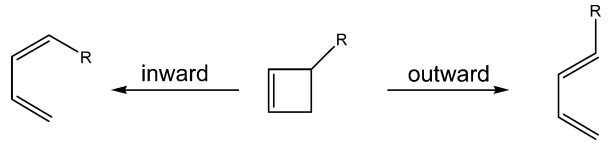
Abstract: Recent reports of inward torquoselectivities in thermal electrocyclic ring-opening reactions of 3-silylcyclobutenes have revealed that saturated silyl substituents, just like the extensively studied π-acceptors, can exert contrasteric effects. The origins of torquoselectivity for substituents lacking π orbitals have been explained using B3LYP density functional calculations. Orbital interactions involving the substituent vacant orbitals and the occupied orbitals associated with the breaking bonds are found to control these contrasteric torquoselectivities, with minor contributions from electrostatic effects. Reaction energetics and transition states for electrocyclic ring-opening reactions of 3-silyl, fluorosilyl, difluorosilyl, trifluorosilyl, methylsilyl, methyl, fluoromethyl, difluoromethyl, trifluoromethyl, ammonio, phosphonio, formyl, and borohydrido cyclobutenes are reported to complement previous extensive studies of unsaturated substituents. Inward stereoselectivities are predicted for various silyl and phosphonium substituents, along with potent π-acceptors studied earlier. Cope and Diels−Alder reactions involving silyl substituents are also computed.

Introduction

Every electrocyclic reaction can occur by two orbital symmetry allowed stereochemical modes. "Torquoselectivity" is the preference for one of these modes, to form either the "inward" or the "outward" products as illustrated in Scheme 1. In the 1980s, a theory to explain and predict torquoselectivities was developed.[1,2] Since then, a number of predictions have been made and verified in the case of cyclobutene ring-openings, and a general understanding of torquoselectivity in many types of reactions has been established.[3−5] In general, the substituents explored experimentally and theoretically have been unsaturated groups with π systems, halogens with lone pairs, or alkyl groups that exerted an influence through steric effects.

Scheme 1



Recently, Murakami and co-workers reported several examples of preferences for inward rotation of 3-silyl substituents in cyclobutene ring-openings.[6] We have carried out computations on a variety of new silyl-substituted electrocyclic reactions of cyclobutenes as well as some additional neutral and charged model systems, to determine which of the various theories that have been proposed to explain the unusual contrasteric stereoselectivities observed in the Murakami reactions are correct.[6] Previous theoretical explorations have involved the role of π and π^* orbitals in stabilizing the transition states.[1−5] However, in this study, the role of σ and σ^* orbitals in the ring-opening transition states is investigated. We have also explored the Cope rearrangement and Diels−Alder reaction involving silyl substituents and address explanations for stereoselective substituent effects proposed by Inagaki.[7,8]

Background

For electrocyclic ring-opening reactions of substituted cyclobutenes, Rondan and Houk discovered that donors rotate away from the breaking bond preferentially, while strong acceptors rotate inward.[1,2,4] As sketched in Scheme 2, they

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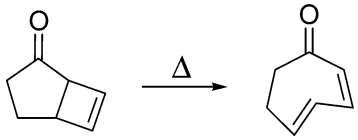
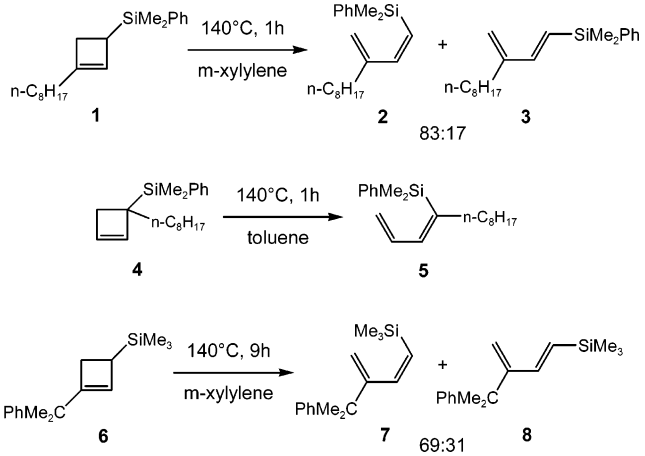
Scheme 2. Model for Torquoselectivity of Donor and Acceptor Substituents in Cyclobutene Ring-Opening Transition States According to Rondan−Houk[1,2,4]

Scheme 3. Thermal Ring-Opening of Bicyclo[3.2.0]-hept-6-en-1-one to Cyclohepta-2(*Z*),4(*E*)-dien-1-one[9]



Scheme 4

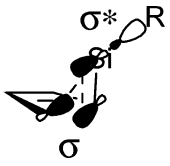


proposed that a filled orbital of a donor substituent experiences closed-shell repulsion upon inward rotation and, therefore, the substituent prefers to rotate outward. By contrast, a vacant acceptor orbital on the substituent was predicted to promote inward rotation to maximize orbital interactions between the filled orbital of the breaking bond and the vacant orbital of the substituent. The inward rotation of a formyl substituent in the ring-opening of 3-formylcyclobutene[3a] and inward rotation of *tert*-butyl in 3-*tert*-butyl-3-methoxycyclobutene[5] (driven by outward rotation of the stronger donor, methoxy) are particularly striking examples of the dominance of electronic over steric effects and were predicted before the experimental determinations. A great many examples consistent with this picture have been found: for example, the surprising stereoselectivity recently discovered in bicyclo[3.2.0]hept-6-en-2-ones (Scheme 3) can be explained by the preferential inward rotation of the acceptor ketone rather than the donor alkyl substituent.[9]

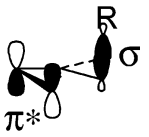
Recently, Murakami et al. reported reactions of various trialkylsilyl-substituted cyclobutenes, shown in Scheme 4. A mixture of **1** and **4** was found to produce **2**, **3**, and **5**. The ratio of **2**:**3**, which resulted from **1**, was found to be 83:17. Compound **6** formed **7** and **8** in a 69:31 ratio with a 95% overall yield.[6] Elegant applications in synthesis were also reported.[10]

To explain these results, Murakami et al. proposed that the preference for inward rotation of the silyl substituent results from favorable overlap of low-lying σ^* orbitals of the silyl substituent with the occupied orbital of the breaking bond in the inward-rotating transition state. This is shown schematically in Scheme 5. Density functional calculations on a model system, the ring-opening of 3-silylcyclobutene, were offered in support of this explanation. Calculations suggest that the activation energy of the inward rotation is 1.7 kcal/mol lower than the barrier for outward rotation.[6]

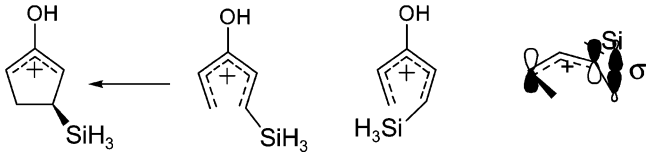
Scheme 5. Model for Torquoselectivity of Silyl Substituents in Cyclobutene Ring-Opening Transition States According to Murakami



Scheme 6. Model for Torquoselectivity of Donor and Acceptor Substituents in Cyclobutene Ring-Opening Transition States According to Inagaki



Scheme 7



Inagaki proposed an alternative explanation for this phenomenon[11] based upon his studies of the role of C−Si hyperconjugation in other pericyclic reactions.[7,8] For a variety of cycloadditions and electrocyclic reactions, Inagaki analyzed the orbital interactions and proposed that there is a preference for overlap of C−Si, or other high-lying σ orbitals involving electropositive elements, with the forming butadiene π^* orbital (Scheme 6). He studied the interbond populations at the ring-opening transition state of cyclobutenes to justify this proposal.[7,8]

We also considered the possibility that partially or fully charged substituents could influence torquoselectivity through electrostatic effects, with partially positive groups rotating inward toward the electron-rich C_4-terminus and negatively charged groups rotating outward.

In a different system, Smith et al. found torquoselectivity involving Nazarov cyclizations (Scheme 7).[12] They studied computationally the effect of inner (*Z*) and outer (*E*) silyl groups on the barriers of cyclizations of protonated 1,4-pentadien-3-one. Silyl substituents favor inward rotation in the reverse of Nazarov-type cyclizations. This was attributed to carbon−silicon hyperconjugation with the π system in the inward-rotating transition state.[13,14] Denmark found a related effect of allylic silyl substituents.[15]

Computational Methods

Calculations with the Becke3LYP functional and the 6-31G(d) basis set using the Gaussian 98 software[16] were carried out to locate transition states for inward and outward electrocyclizations of substituted cyclo-

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butenes and the transition states for silyl-substituted Diels−Alder reactions and Cope rearrangements. Energetics reported are of optimized, zero point corrected, electronic energies of the most stable conformation of cyclobutene derivatives and transition states. Energetics reported for Cope and Diels−Alder reactions are also for the most stable conformations unless otherwise stated. Single points on B3LYP/6-31G(d) optimized geometries with B3LYP/6-311++G(3d,3p) were also carried out to compare energetics of different basis sets.

Frontier molecular orbital diagrams were generated with restricted Hartree−Fock calculations with the 6-31G(d) basis set using Spartan.[17] Hartree−Fock orbitals provide a direct correspondence with ionization potentials and electron affinities through Koopmans' theorem and are useful for frontier orbital discussions.[18] Spartan was also used to generate the electrostatic potential surfaces for various substituted ring-opening transition states of cyclobutenes. Electrostatic charges were calculated with HF/6-31G(d) and are fitted as point charges to the electrostatic potential.

Results and Discussion

To clarify the orbital description of torquoselectivity, Figure 1 illustrates an orbital correlation diagram for the conversion of cyclobutene to butadiene by the allowed conrotatory path. This figure is an elaboration of the orbital correlations by Woodward and Hoffmann[19] and also by Longuet-Higgins and Abrahamson,[20] who showed that stereospecificity may be rationalized by correlations of π, π^*, σ, and σ^* orbitals of cyclobutene with the two π and two π^* orbitals of butadiene. This correlation diagram has also been used to help explain torquoselectivity by consideration of the correlation of reactant orbitals with those of the transition state and the transition state with those of the s-cis product.[3m] The conrotatory ring-opening retains C_2 symmetry throughout the reaction. At the transition state, the HOMO and LUMO are not the π and π^* frontier molecular orbitals of cyclobutene, but the distorted σ and σ^* orbitals. The σ orbital of the breaking bond of cyclobutene becomes the HOMO of the transition state. On the other hand, the σ^* of the breaking bond of the reactant correlates with the LUMO of the transition state. Donor and acceptor substituents can facilitate bond breaking by orbital mixing with these σ and σ^* FMOs, respectively.

As described in earlier publications, the substituent effect on outward rotation is related to the interactions of substituent orbitals with those of the breaking bond.[3] In general, both donors and acceptors lower activation energies for outward rotations:

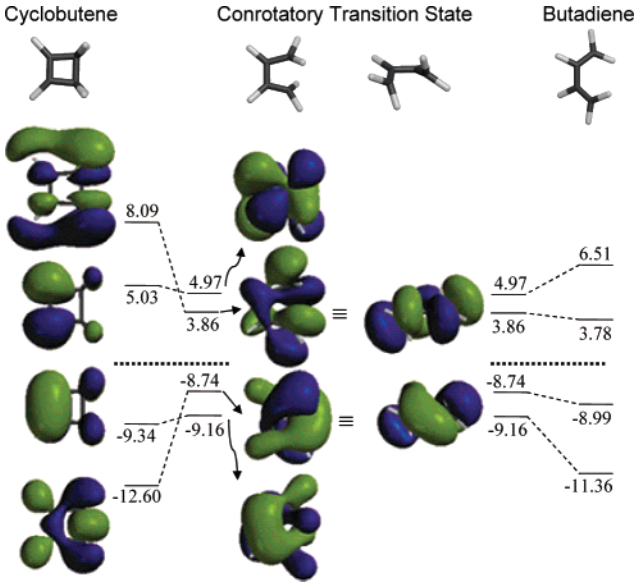

Figure 1. Correlation of frontier orbitals of cyclobutene with those of the conrotatory transition state and the product, butadiene (HF/6-31G(d)).

Table 1. Literature Values of Calculated Activation Energies (kcal/mol) for Outward and Inward Electrocyclic Ring-Opening of 3-Substituted Cyclobutene[3j,k]

	RHF/6-31G(d)//3-21G *RHF/6-31G(d)//3-21G(d)*			MP2/6-31G(d)// 3-21G+ZPE
−R	$\Delta E_{out}^{\ddagger}$	$\Delta E_{in}^{\ddagger}$	$\Delta\Delta E_{(in-out)}^{\ddagger}$	$\Delta\Delta E_{(in-out)}^{\ddagger}$
H	41.6	41.6	0.0	
OLi	27.8	52.2	24.4	
NH_2	34.7	52.2	17.5	
OH	37.4	54.6	17.2	
F	42.0	58.9	16.9	15.1
Cl	*46.6*	*60.2*	*13.6*	
SH	*41.3*	*55.0*	*13.7*	
Me	44.5	51.3	6.8	5.3
$HCCH_2$	40.4	45.3	4.9	
CO_2^-	39.8	47.1	7.3	
NH_3^+	46.3	54.2	7.9	
$CHNH_{trans}$	42.3	39.3	−3.0	
$CHNH_{cis}$	42.6	45.6	3.0	
S(O)H	*45.3*	*45.4*	*0.1*	
CCH	40.6	48.2	7.6	
SO(OH)	*46.6*	*45.2*	*−1.4*	
CF_3	48.3	50.9	2.6	
SO_2H	*42.5*	*42.2*	*−0.3*	
CN	42.9	47.2	4.3	4.2
CO_2H	41.9	44.2	2.3	
NO_2	42.8	50.1	7.3	
COMe	41.4	42.6	1.2	
CHO	42.6	38.0	−4.6	−4.7
NO	41.7	39.1	−2.6	−4.7
$CO_2H_2^+$	35.2	30.4	−4.8	
$B(Me)_2$	40.5	29.0	−11.5	
$CHNH_2^+$	34.8	24.7	−10.1	
BH_2	39.0	20.8	−18.2	−18.7

conrotatory transition structures have both high-lying HOMOs and low-lying LUMOs, and both donor and acceptor substituents stabilize the transition structure. Consequently, the interaction with either donor or acceptor substituents will be very strong in the transition state.

Table 1 lists the previously studied ring-opening process of 3-substituted cyclobutenes with primarily unsaturated substituents or those with lone pairs, and the effects on torquoselectivity.[3k] These calculations were carried out with HF and MP2 methods before the rise of DFT methods. The substituents

(16) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head−Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.9; Gaussian, Inc.: Pittsburgh, PA, 1998.
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Table 2. Activation Energies (kcal/mol) for Outward and Inward Electrocyclic Ring-Opening and Substituent LUMO Energy (eV)[21−24]

–R	$\Delta H_{out}^{\ddagger}$ B3LYP/6-31G(d)	$\Delta H_{out}^{\ddagger}$ exp	$\Delta H_{in}^{\ddagger}$ B3LYP/6-31G(d)	$\Delta\Delta H_{(in-out)}^{\ddagger}$ B3LYP/6-31G(d)	$\Delta\Delta H^{\ddagger}$ B3LYP/6-311++(3d,3p)	$\Delta\Delta H^{\ddagger}$ exp	LUMO ϵ (eV) of substituent[24]
−H	33.8	32.5[21]	33.8	0.0	0.0		
−CHO	29.2		25.3	−3.9	−3.8	<-2.7[3b]	4.0
$-CH_3$	31.4	31.6[22]	37.3	5.9	6.5	>4[3a]	7.0
$-CH_2F$	32.2		34.2	2.0	2.2		6.8
$-CHF_2$	34.0		34.3	0.3	0.5		6.9
$-CF_3$	34.5	35.5[3a]	36.8	2.3	2.6	>2.3[3a]	7.3
$-SiH_3$	32.2		30.6	−1.6	−1.5		4.6
$-SiH_2F$	32.2		26.9	−5.3	−4.7		3.5
$-SiHF_2$	32.6		26.6	−6.0			4.0
$-SiF_3$	32.4		28.3	−4.1	−3.8		4.9
$-SiMe_3$	31.9		30.6	−1.3	−1.0	−0.7[24]	5.5
$-NH_2$	20.7		35.4	14.7	16.0		6.1
$-NH_3^+$	33.0		39.3	6.3	6.2		−1.8
$-PH_2$	29.7		33.8	4.1	4.2		4.6
$-PH_3^+$	30.4		29.6	−0.8	−1.6		−2.0
$-BH_2$	25.8		9.9	−15.9	−15.0		2.4
$-BH_3^-$	24.8		69.8	35.0			14.9

that produce inward torquoselectivity are imino, sulfinic acid, sulfonyl, formyl, nitroso, protonated carboxyl, protonated imino, boryl, and dimethylboryl cyclobutenes, all strong π-acceptors. The torquoselectivity for these systems was attributed to the low-lying LUMO of the substituents and strong stabilization from overlap with the HOMO of the TS upon inward rotation.[3k] These results have been described extensively in previous publications[1−5] and do not warrant further discussion here.

Table 2 summarizes the calculations on new systems that were carried out in this study. B3LYP/6-31G(d) data were listed here for some previously studied systems as well for direct comparisons with these new results.

The 33.8 kcal/mol activation barrier for the parent system obtained by B3LYP methods is comparable to the 32.5 kcal/mol obtained by experiment.[21] As predicted and verified experimentally previously,[3b] the formyl-substituted system has a lower activation barrier than the parent system for outward rotation and favors the inward rotation by 3.9 kcal/mol over the outward. This is comparable to the $\geq$2.7 kcal/mol selectivity for inward rotation obtained by experiment.[3b] Similarly, the methyl, trifluorosilyl, amino, and boryl results agree with those computed before and with experiment, where available.

Relative to methyl-substituted cyclobutene ring-opening, fluorination of 3-methyl cyclobutene results in an increase of the outward ring-opening barrier, primarily due to a reduced hyperconjugative ability of the substituents and reduced mixing with LUMO of the TS. Consequently, the inward activation energy decreases from CH_3 to CHF_2 and CH_2F, due to the increasing acceptor nature of the substituents. For the CF_3-substituted system, the inward activation energy is larger than the mono- and difluorinated cases due to the electrostatic repulsion between the fluorinated substituent and the π-system of the cyclobutene.

The focus of this study, derivatives of 3-silylcyclobutenes, has an outward activation energy that is 1.2−1.9 kcal/mol lower than the parent cyclobutene ring-opening with $SiHF_2$ and $SiMe_3$ substituents, respectively. Overall, fluorination of a silyl substituent has little effect on the outward activation energy ($\pm$0.4 kcal/mol). The increased diffuseness of the silyl relative to methyl accounts for this smaller effect in activation energy upon fluorination.

There is a greater effect on the inward activation energy upon fluorination of silyl-substituted systems than on the outward activation energy. Silyl substitution has an inward transition state that is 3.2 kcal/mol more stable than the ring-opening of the parent cyclobutene. Silyl substitution also equates to an inward activation energy that is 6.7 kcal/mol lower than the inward activation energy of a methylcyclobutene. Fluoro- or bisfluorosilyl-substituted cyclobutene has an inward activation energy that is approximately 4 kcal/mol lower than silylcyclobutene ring-opening. Trimethylsilyl and silylcyclobutenes have equal inward activation energies (30.6 kcal/mol). The trend that is apparent for silylcyclobutenes is that addition of a fluorine initially decreases the inward activation energy but the addition of a third fluorine to the silyl increases the inward activation energy due to electrostatic repulsion between the fluorine and the electron-rich π bond in cyclobutene in the transition state. The torquoselectivity value ($\Delta\Delta H_{(in-out)}^{\ddagger}$) exhibits a similar trend for the fluorosilyl cyclobutenes as for the inward activation energy. Consequently, the torquoselectivity for silylcyclobutenes is dependent on the stability of inward transition states rather than the outward transition states.

For 3-aminocyclobutene, the substituent substantially stabilizes the outward rotating transition structure when compared to cyclobutene, as evidenced by the drop from 33.8 kcal/mol for the parent to 20.7 kcal/mol for the 3-amino derivative. This is a result of the lone pair of the amine substituent, which is lined up to overlap with the σ^* orbital of the breaking bond, stabilizing the outward transition state. The enormous preference for outward rotation, by 15 kcal/mol, is in accord with earlier calculations.[3] Upon protonation of the amine, this stabilization is lost, and there is an increase by 12.3 kcal/mol of the outward activation energy. This value is now comparable to that for the 3-methylcyclobutene ring-opening (33.0 and 31.4 kcal/mol, respectively).

In the inward transition state for the aminocyclobutene ring-opening, the lowest energy conformation has the lone pair of the amino group facing away from the breaking σ bond to avoid an unfavorable antiaromatic situation if the lone pair was overlapping the breaking σ bond. Furthermore, with the lone pair anti to the breaking σ bond, there is overlap between the lone pair and the forming π bond at C_3 (Figure 2A). Upon protonation, these effects are eliminated, and there is an increase

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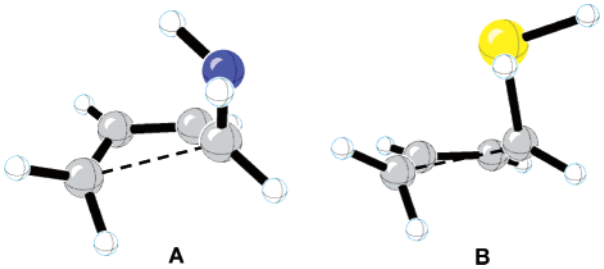

Figure 2. Inward ring-opening transition structure of aminocyclobutene (**A**) and phosphonylcyclobutene (**B**).

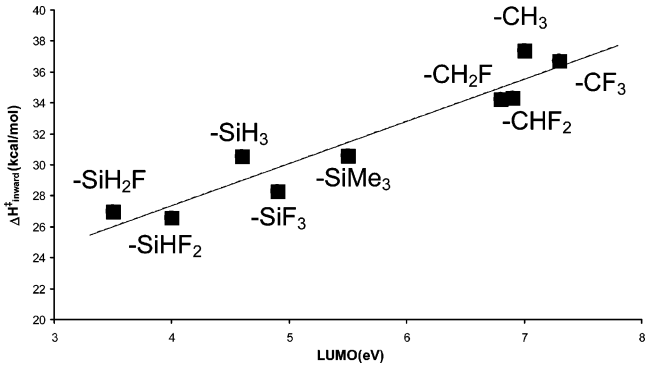

Figure 3. Plot of $\Delta H_{\text{inward}}^{\ddagger}$ (B3LYP/6-31G(d)) versus the substituent LUMO energy (HF/6-31G(d)).

in $\Delta H_{\text{inward}}^{\ddagger}$. Consequently, there is greater destabilization of the outward transition state relative to the inward upon protonation of the amino substituent, but not such that there is a switch in the torquoselectivity from outward to inward for the protonated 3-aminocyclobutene.

On the other hand, $\Delta H_{\text{inward}}^{\ddagger}$ decreases for phosphino upon protonation. There is little or no overlap between the breaking σ bond and the phosphino substituent. The lone pair of phosphine is essentially the 3s orbital of the P. This is also the reason the H's are anti to cyclobutene for phosphino, rotated 120° relative to the amine substituent (Figure 2B). Upon protonation, there is loss of unfavorable interactions in the inward rotation transition structure, and also the σ^* orbitals of the PH_3 group are lowered, and a decrease in $\Delta H_{\text{inward}}^{\ddagger}$ for the phosphonium system as compared to the phosphine system is observed. For the outward ring-opening activation energy, there is only a 0.7 kcal/mol increase because the phosphino substituent does not stabilize the breaking σ^* as in the amino-substituted case.

Substituents, such as formyl and other previously studied systems with low-lying π^* orbitals, prefer inward rotation as evidenced by the $\Delta\Delta H^{\ddagger}$ values in columns 5 and 6 of Table 2.[3] Silyl and protonated phosphinyl may prefer inward rotation by any, or a combination of the effects described earlier: (1) σ^* overlap with the distal terminus of the breaking bond; (2) the overlap of the C−Si σ^* with the π system (as in the case of Nazarov-type cyclizations); (3) the Inagaki overlap of the C−Si σ with the π^* orbital at the distal terminus of the breaking bond; or (4) the attraction of the partially positive substituent with the electron density on the distal terminus of the breaking bond.

Figure 3 is a plot of the LUMO (σ^*) energies of the substituents (calculated for the simple hydrocarbon HR for each substituent, R) versus the activation energy for inward rotation ($\Delta H_{\text{inward}}^{\ddagger}$) for 3-*R*-cyclobutenes. Figure 3 illustrates a trend between the LUMO energy and the inward activation energy.

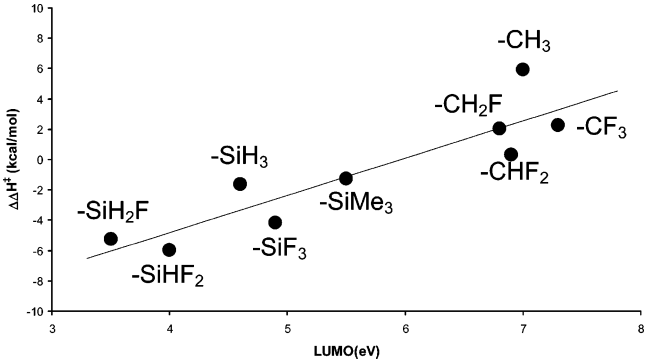

Figure 4. Plot of $\Delta\Delta H^{\ddagger}$ ($\Delta H_{\text{inward}}^{\ddagger} - \Delta H_{\text{outward}}^{\ddagger}$) versus the substituent LUMO energy (HF/6-31G(d)).

As the LUMO energy increases, the activation energy for inward rotation increases. The net effect of fluorination of a silyl substituent results in a greater change in inward activation than fluorination of a methyl substituent, as illustrated by the greater dispersion of SiF_nH_m data points relative to CF_nH_m data points. Addition of the first fluorine to a methyl or a silyl cyclobutene lowers the LUMO and also lowers the inward activation energy. The second fluorine increases the LUMO of the substituent and results in a slight decrease in inward activation for the silyl and a slight increase for the inward ring-opening for methylcyclobutene. The third fluorine results in an increase in the LUMO energy and the inward activation energy for both silyl and methyl substituents. Trimethylsilylcyclobutene ring-opening has a higher inward activation energy than the fluorinated silyl cyclobutene ring-openings and equally has a higher LUMO energy. There is a clear correlation between the LUMO and the inward activation energy for fluorinated silyl and fluorinated methyl substituents, which therefore supports that the $\sigma-\sigma^*$ effects dominate in inward ring-opening.

Figure 4 is a plot of the difference between inward and outward rotation activation energies ($\Delta\Delta H^{\ddagger}$) versus the LUMO energy of the substituents. As in the previous correlation (Figure 3), there is a greater dependence of the LUMO energies for silyl-substituted systems as compared to the methyl-substituted systems for inward torquoselectivity. Furthermore, as in the previous correlation (Figure 3), there is also a clear correlation between the LUMO energies and the difference in activation energies for fluorosilyl- and fluoromethyl-substituted cyclobutene ring-openings. This correlation further supports that the torquoselectivity is dependent on the inward activation energies because the correlation in Figure 4 is very similar to the correlation illustrated in Figure 3.

Additional support for the role of the substituent σ^* orbital comes from the relationship between the distance between the substituent X (C or Si) and the distal terminus (C_4) of the breaking σ bond, and the activation energy for inward rotation. Figure 5 is a graph that plots the correlation between the C_4-X bond length versus the inward activation for silyl substituents, as well as for methyl substituents. The trend that is illustrated here is that as this distance decreases between the C_4-X, the inward ring-opening activation energy decreases. Relative to the fluorinated methyl substituents ($R^2 = 0.84$), there is a better correlation for the fluorinated silyl substituents ($R^2 = 0.96$), presumably because the C−C bond is shorter than a C−Si bond and there is less flexibility for the methylated transition structure than the silyl transition structures as evidenced by the distance

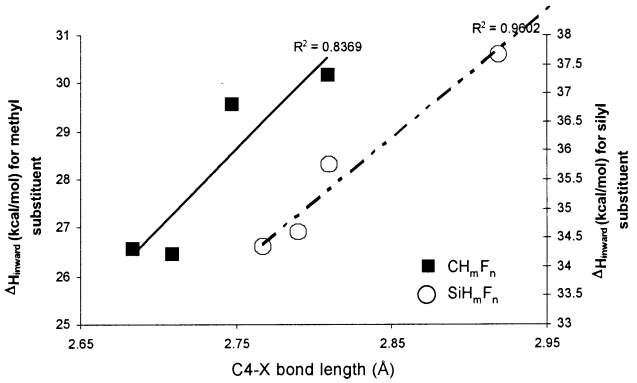

Figure 5. Plot of substituent C_4-X distance (X = substituent C or Si) versus both $\Delta H_{inward}^{\ddagger}$ for the CH_mF_n system and $\Delta H_{inward}^{\ddagger}$ for the SiH_mF_n system (B3LYP/6-31G(d)). X = C, Si.

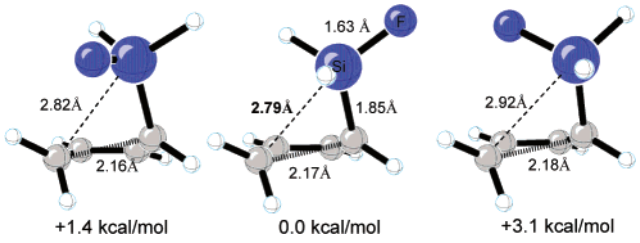

Figure 6. Possible rotamers of inward transition state of $-SiH_2F$-substituted cyclobutene. The most stable is one with Si−F σ^* antiperiplanar to the breaking σ bond of the distal terminus (middle).

between C_4-X (±0.13 Å for X = C, ±0.15 Å for X = Si). In summary, as the distance between C_4-X decreases, where X is the center atom of the substituent, the $\Delta H_{inward}^{\ddagger}$ decreases. This suggests that larger $\sigma-\sigma^*$ interactions decrease C_4-X distances and stabilize the transition state. This trend is consistent with the Murakami hypothesis.

The conformational dependence of the substituents on the energies of activation was also tested, to determine if there is a relationship between the orientation of the substituent σ^* orbitals with respect to the breaking bond, and the facility of inward rotation. Several rotamers of the inward transition structures of fluorosilyl-substituted cyclobutene ring-opening were explored, with the $F-Si-C_3-C_4$ torsional angle staggered, or approximately ±60° or 180°. These three rotamers are illustrated in Figure 6. With respect to the most stable fluorosilylcyclobutene conformer, the middle structure has an energy of 26.9 kcal/mol, the structure on the left has an energy of 28.3 kcal/mol, and the structure on the right has an energy of 30.0 kcal/mol. The rotamer which has the Si−F σ^* antiperiplanar to, and lined up to interact with, the breaking σ bond is the most stable transition state. This supports the Murakami postulate because the $\sigma^*_{Si-F}-\sigma_{C-C}$ overlap is highest in the favored TS, while the others involve $\sigma^*_{Si-H}-\sigma_{C-C}$ overlap, which will be somewhat less stabilizing.

The possible role of electrostatic effects on torquoselectivity was also studied. Figure 7 shows the electrostatic potential in a sampling of inward transition states. A silyl substituent is a better acceptor than a methyl, and this is shown as a bluer color on the substituent and the greater positive charge of the substituent. Addition of fluorine to a methyl substituent increases the positive electrostatic potential at the substituent C, which is aligned to interact with the distal terminus of the breaking bond. As the substituent region becomes bluer and the point charge becomes

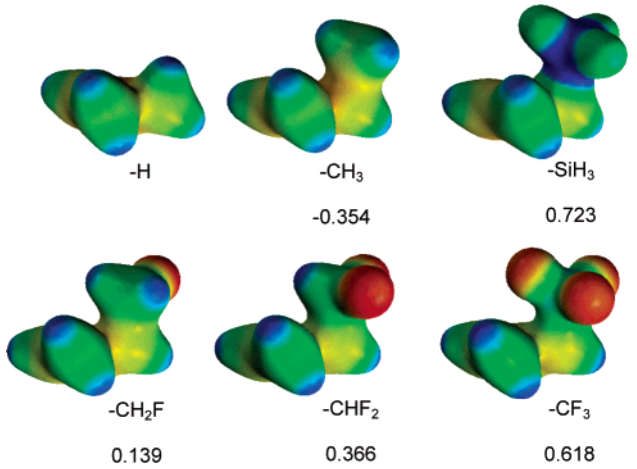

Figure 7. Electrostatic potential of inward rotating ring-opening transition structures of cyclobutene and substituted cyclobutene systems. Red corresponds to the negative electrostatic potential, and blue corresponds to the positive potential. The numbers correspond to the fitting point charges to electrostatic potential at the 3-substituent C or Si.

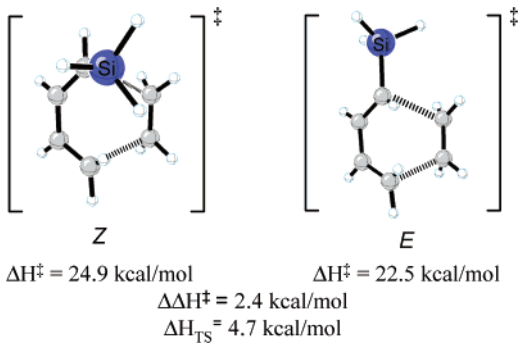

Figure 8. Activation energies for the Diels−Alder reactions of (*Z*)- and (*E*)-1-silylbutadiene with ethylene (B3LYP/6-31G(d)).

greater, there is a decrease in $\Delta H_{inward}^{\ddagger}$. For methyl substituents, addition of fluorine results in a net decrease in $\Delta H_{inward}^{\ddagger}$ until the addition of a third fluorine, where the $\Delta H_{inward}^{\ddagger}$ increases. This is attributed to an electrostatic repulsion between the inner F and the breaking σ bond. The net effect of protonation or fluorination is the same, in that the torquoselectivity preference for outward rotation is decreased. For silyl-substituted systems, inward selectivity increases upon fluorination except for SiF_3 due to sterics/electrostatic repulsion. Although electrostatic effects could play a role in determining torquoselectivity, substituents such as the protonated amine substituent, which is positively charged, have a torquoselectivity similar to that of methyl, which is not positively charged. Electrostatic effects parallel torquoselectivity, but are likely to be a minor factor in the control of stereoselectivities as compared to orbital interactions.

A Cope rearrangement and Diels−Alder reaction with silyl substituents were examined to test whether the Murakami−Rondan−Houk postulate can be applied to these systems and also to test Inagaki's earlier proposal that these systems supported the donor-π^* hypothesis.[7,8] B3LYP/6-31G(d) calculations were carried out here on cycloadditions of silyl-substituted *E* and *Z* butadiene with ethylene. Transition state and activation energies are shown in Figure 8 and are relative to the corresponding *Z* and *E* dienes with ethylene. The transition state of the Diels−Alder reaction with the *E* diene is more stable than that with the *Z* diene by 4.7 kcal/mol, and the activation

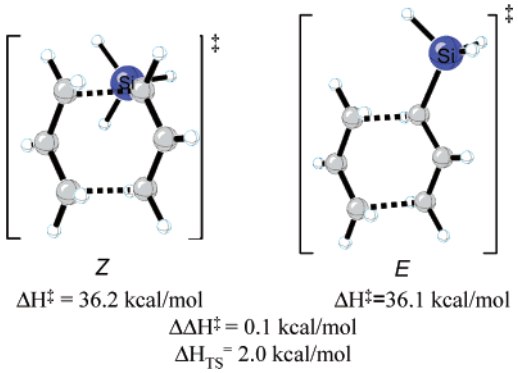

Figure 9. Energetic profile of the Cope reaction of the silyl-substituted system (B3LYP/6-31G(d)).

energy of the Diels−Alder reaction with the *E* configuration is 2.4 kcal/mol lower than that with the *Z* configuration.

These results are provided to supplement studies carried out by Inagaki and Ikeda where they argue that the electron-donating σ bonds at the *Z*-positions enhance the reactivity more than those at the *E*-positions.[7] In their study, they support their claim by presenting data of the activation energy of Diels−Alder reactions of *E*- and *Z*-isomers of 2-silyl-2,4-pentadiene with ethylene. They find that the *Z*-isomer has an activation energy that is 2.8 kcal/mol lower than the *E*-isomer with B3LYP/6-31G(d) calculations. They also found that the *E*- and *Z*-isomers of 2,4-pentadiene with ethylene result in the *E*-isomer having an activation energy that is 5.5 kcal/mol lower than that of the *Z*-isomer. Hence, it can be argued that the enhancement of rate of a Diels−Alder reaction for (*Z*)-2-silyl-2,4-pentadiene with ethylene is a result of the competition between the methyl and silyl substituents, where methyl favoring the *E*-isomer by 5.5 kcal/mol wins over the silyl favoring the *E*-isomer. Results illustrated in Figure 8 clearly indicate that the silyl group favors the *E*-position over the *Z*-position. This is contrary to Inagaki and Ikeda's claim that 1-substituted butadienes with a better acceptor substituent at the *Z*-position are more reactive than those at the *E*-position, because silyl groups, if categorized as electropositive (better acceptor) as by Inagaki, are more reactive in the *E*-position.

Exploration of the Cope reactions for silyl *E*- and *Z*-substituted 1,5-hexadienes was also carried out. The *E* configuration is favored by 0.1 kcal/mol for 1-silyl-1,5-hexadiene (Figure 9). The difference in absolute energies of the (*Z*)- and (*E*)-1-silyl-1,5-hexadiene transition states (ΔH_{TS}) is only 2 kcal/mol. There is a very small preference for the silyl group to be in the *E* configuration as compared to the *Z*.

Ingakaki has previously studied similar systems and has found that the *Z* transition state of 1-methyl-1-silyl-1,5-hexadiene is more stable by 1.0 kcal/mol ($\Delta\Delta H^{\ddagger}$),[25] whereas 1-methyl-1,5-hexadiene prefers the *E* transition state by only 0.4 kcal/mol ($\Delta\Delta H^{\ddagger}$). The differences in the absolute energies between the transition state of *E* and *Z* conformations for these two systems are −0.5 and 2.0 kcal/mol, respectively, where the negative value indicates a more stable *Z* configuration.[26] Inagaki's

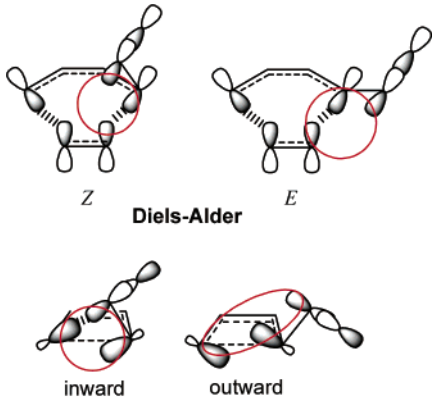

Figure 10. Orbital diagram of the two possible transition structures for the Diels−Alder reaction (*E* and *Z*) and cyclobutene ring-opening (inward and outward).

argument for the trend is that the silyl group is an electron-donating σ bond, which facilitates such rearrangement products. They did not report results for 1-silyl-1,5-hexadiene. The *A* value for silyl is 1.45 kcal/mol,[27] whereas the *A* value for methyl is 1.74 kcal/mol.[28] Also, the *A* value for trimethylsilyl is 2.4−2.6 kcal/mol.[29] whereas the *A* value for *tert*-butyl is 4.9 kcal.[30] The *A* value, which quantifies the preference for axial or equatorial positions in a cyclohexane, shows that silyl is actually somewhat smaller than methyl in this environment and that trimethylsilyl is also smaller than a *tert*-butyl in this environment. The preference for pseudoaxial silyl groups here is a simple steric effect.

Both of these results regarding Cope and Diels−Alder reactions are in contrast to previous models for reactions of this type.[7,8] Indeed, the factors influencing torquoselectivity in cyclobutenes cannot operate here, because there is no twisting motion and hence no torque in the forming or breaking C−C bonds. The situations are illustrated in Figure 10. The two different transition states of Diels−Alder, the *Z* and *E* configurations, have similar overlap between the p orbitals of the dienophile with the σ bond of the diene and substituent. Alternatively, there is a similar interaction between the p orbital of the dienophile with the p orbital of the diene and the σ^* of the substituent, which is indicated by the red circles. However, in the cyclobutene ring-opening, the overlap between the breaking σ and the σ between the cyclobutene and the substituent (or σ^* of the substituent) is significant for the inward (red circle), while it is absent in the outward. Consequently, neither the geminal bond model nor the Murakami−Rondan−Houk model is applicable to the prediction of the stereoselectivity of the Cope or Diels−Alder reactions.

Conclusion

Various explanations for the torquoselectivity of silyl-cyclobutene ring-openings have been investigated theoretically. As the energy of the σ^* orbital of the substituent is lowered, torquoselectivity is strongly affected, and inward rotation becomes favored. The results reported here are consistent with

(22) Frey, H. M.; Marshall, D. C. *Trans. Faraday Soc.* **1965**, *61*, 1715−1721.
(23) Orbital energies are from HF/6-31G(d) calculations.
(24) Value of $\Delta\Delta G^{\ddagger}$ for trimethyl[3-(1-methyl-1-phenylethyl)-2-cyclobuten-1-yl]-silane (ref 6).
(25) As stated in ref 26, $\Delta\Delta H^{\ddagger} = \Delta HZ^{\ddagger} - \Delta HE^{\ddagger}$ and ΔHTS = H(Z)TS − H(E)TS.
(26) Ikeda, H.; Naruse, Y.; Inagaki, S. *Chem. Lett.* **1999**, 363−364.
(27) Penman, K. G.; Kitching, W.; Adcock, W. *J. Org. Chem.* **1989**, *54*, 5390−5391.
(28) Booth, H.; Everett, J. R. *Chem. Commun.* **1976**, 278−279.
(29) Kitching, W.; Olszowy, H. A.; Drew, G. M.; Adcock, W. *J. Org. Chem.* **1982**, *47*, 5153−5156.
(30) Monoharan, M.; Eliel, E. L. *Tetrahedron Lett.* **1984**, *25*, 3267−3268.

the role of the substituent vacant σ^* orbital in cyclobutene ring-opening. Evidence for this effect includes the relationship between the LUMO of the substituent and $\Delta\Delta H^{\ddagger}$, as well as the relationship between the distance of the substituent to the distal terminus of the breaking bond and the $\Delta H_{\text{inward}}^{\ddagger}$. There is no such effect in Diels−Alder or Cope reactions, which do not involve the required twisting of partial single bonds. Electrostatic effects parallel the $\sigma-\sigma^*$ effects, but they likely play only a minor role on torquoselectivity. In summary, the Murakami et al. experiments and their explanations of stereoselectivity extend the generality of torquoselectivity to substituents with low-lying σ^* orbitals.

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Supporting Information Available: Cartesian coordinates and energetics for all reactant and transition structures (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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