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Predominance of the Participation of the Geminal over Vicinal Bonds: Torquoselectivity of Retro-Nazarov Reactions

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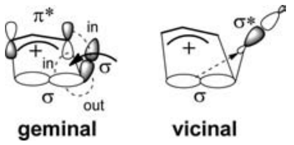
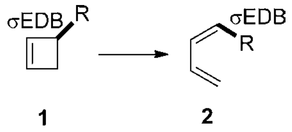
ABSTRACT



Torquoselectivities of electrocyclic ring-opening reactions have been proposed to be controlled by the participation of electron-donating σ-bonds (σ-EDB) geminal to the breaking σ-bond and/or vicinal electron-accepting σ-bonds (σ-EAB) or lone pair(s) of the substituent(s). We designed reactions in which the effects of the vicinal bonds should be significantly diminished by the cationic nature of the reactants. The calculated enthalpies of activation of the retro-Nazarov reactions of some 3-substituted cyclopentenyl cations show inward rotation of the geminal σ-EDB, which is consistent with the theory of geminal bond participation.

We previously proposed a theory of geminal bond participation:[1−6] the σ-bonds geminal to the forming or breaking bonds participate in the chemical reactions via cyclic transition states and control the reactivity and selectivity. This theory was applied to the torquoselectivity of the electrocyclic ring-opening reaction of cyclobutene ring-opening reactions and predicted that the electron-donating σ-bond (σ-EDB) geminal to the cleaving σ-bond participates and rotates inwardly to occupy the *Z*-position (Scheme 1).[3] An orbital phase theory for the torquoselectivity has been developed (Figure 1a).[4] Geminal bond participation was recently generalized by the orbital phase theory.[6]

Scheme 1



Houk et al.[7] proposed that the interaction of the bonding orbital of the breaking σ-bond with the vicinal lone pair(s) or π-bonds was important: attraction between the σ and π^* orbitals of the electron-accepting π-bond (π-EAB) for

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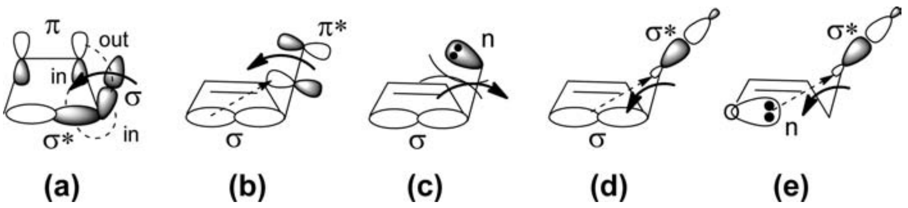
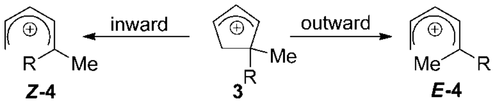


Figure 1. Theories of the torquoselectivity of electrocyclic ring opening.

Scheme 2



***Z*-4** **3** ***E*-4**

inward rotation and repulsion between σ and n of the lone pair(s) for outward rotation (Figure 1b, c).

Murakami[8] extended the Rondan–Houk theory of vicinal bond participation to explain the inward rotation of a silyl group with vicinal σ-EAB (Figure 1d). Shindo and Mori[9] applied the Murakami's σ–σ^* attraction to their oxetene systems and n–σ^* attraction (Figure 1e).

We designed a model reaction, the ring opening of cyclopentenyl to pentadienyl cations (Scheme 2),[10] as a prototype of the retro-Nazarov reaction[11,12] to demonstrate the predominance of geminal over vicinal bond participation. The orbital interactions of the retro-Nazarov reaction are illustrated in Figure 2. Cyclic geminal σ–σ–π^* interaction (Figure 2a) is shown instead of cyclic geminal σ–σ^*–π interaction (Figure 1a), due to the overwhelming electron-accepting power of the cationic allylic moiety. The breaking σ-bond is a donor toward the cationic moiety, but is not a good donor toward a vicinal bond on the substituents because the electrons in the breaking σ-bond delocalize to the cationic π-system. The σ–$\sigma^*(\pi^*)$ interaction (Figure 2b) for vicinal bond participation is weak. Inward rotation is not expected from vicinal bond participation, but from geminal bond participation.

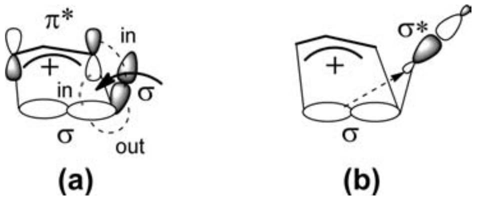


Figure 2. Orbital interactions for (a) geminal and (b) vicinal bond participation in the retro-Nazarov reaction.

Table 1. σ_{CR} Energies (B3LYP/6-31G(d)) and Difference in the Enthalpies of Activation (kcal mol^{-1}) in the Retro-Nazarov Reactions (B3LYP/6-311++G(*3df,2p*)//B3LYP/6-31G(d), ZPE Corrected)

substrate	$E(\sigma_{CR})$	$\Delta H^{\ddagger}_{in}$	$\Delta H^{\ddagger}_{out}$	$\Delta\Delta H^{\ddagger}$[a]
3a (R = BH_2)	−0.729	13.5	27.1	−13.6
3b (R = CH_3)	−0.794	18.9		0.0
3c (R = NH_2)	−0.899	[a]	1.8	[a]
3d (R = OH)	−0.973	14.7	6.5	8.3
3e (R = F)	−1.068	19.4	13.1	6.2
3f (R = SiH_3)	−0.714	23.5	31.8	−8.3
3g (R = PH_2)	−0.779	26.4	27.4	−1.0
3h (R = SH)	−0.815	[b]	[b]	[b]
3i (R = Cl)	−0.882	23.3	18.0	5.3

[a] For the amino derivative **3c**, the IRC calculation from the proposed TS for the inward rotation did not end in **3c**, but the bicyclic compound with another C–N bond (See Supporting Information). [b] We failed to locate **3h** as a local energy minimum.

We calculated[13] the enthalpy of activation for the inward ($\Delta H_{in}^{\ddagger}$) and outward ($\Delta H_{out}^{\ddagger}$) rotations of 4,4-disubstituted substrates **3a**–**3i** with one substituent fixed to a methyl group (Scheme 2) to reduce any unwanted steric bias. As shown in Table 1, the selectivities, which are the differences in the enthalpy of activation ($\Delta\Delta H^{\ddagger} = \Delta H_{in}^{\ddagger} - \Delta H_{out}^{\ddagger}$),

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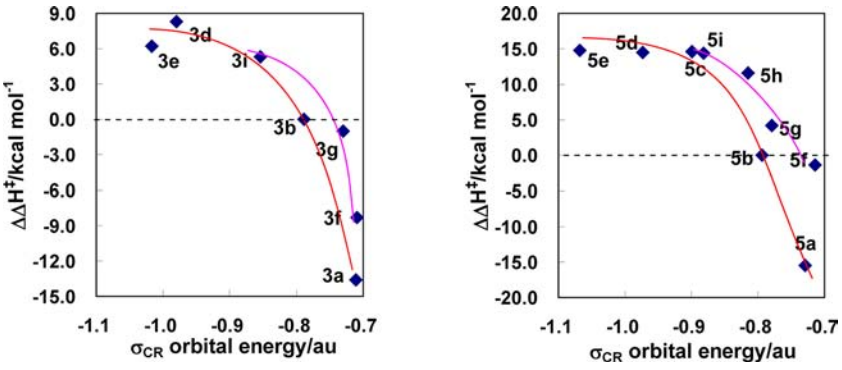
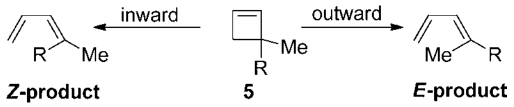


Figure 3. Dependence of the torquoselectivity or $\Delta\Delta H^{\ddagger}$ (B3LYP/6-311++G(*3df,2p*)//B3LYP/6-31G(d), ZPE corrected) on σ_{CR} energy (RHF/6-31G(d)): (a) the retro-Nazarov reactions of **3** (Scheme 2); (b) the electrocyclic ring-opening reactions of 3-methyl derivatives **5** of 3-substituted cyclobutenes **1** (Scheme 3).

Scheme 3



depend on the σ_{CR} orbital energies[14] (Figure 3a). A more negative number means a preference for inward rotation of the substituent relative to methyl. With the σ_{CR} orbital energies in the order σ_{CF} (**3e**) < σ_{CO} (**3d**) < σ_{CC} (**3b**) < σ_{CB} (**3a**) and σ_{CCl} (**3i**) < σ_{CP} (**3g**) < σ_{CSi} (**3f**), the torquoselectivity of outward rotation is lowered and changes to that of inward rotation, which is then enhanced. Outward rotation results from the preferential inward rotation of the methyl group because the σ_{CC} energy for the methyl group is higher than the σ_{CR} energies. The torquoselectivity of the outward rotation is less sensitive to the σ_{CR} orbital energies. This tendency is in good agreement with our prediction based on geminal bond participation and is similar to that (Figure 3b) of the torquoselectivity of the ring-opening reaction of 3-methyl derivatives **5** of cyclobutenes **1** (Scheme 3).[3,5] This result suggests that the vicinal bond participation is not very important.

We calculated at the B3LYP/6-31G(d) level a realistic retro-Nazarov reaction of the 2-hydroxy derivative of 3-pentenyl cation **6** with a silyl group, which has been predicted to show a strong tendency toward inward

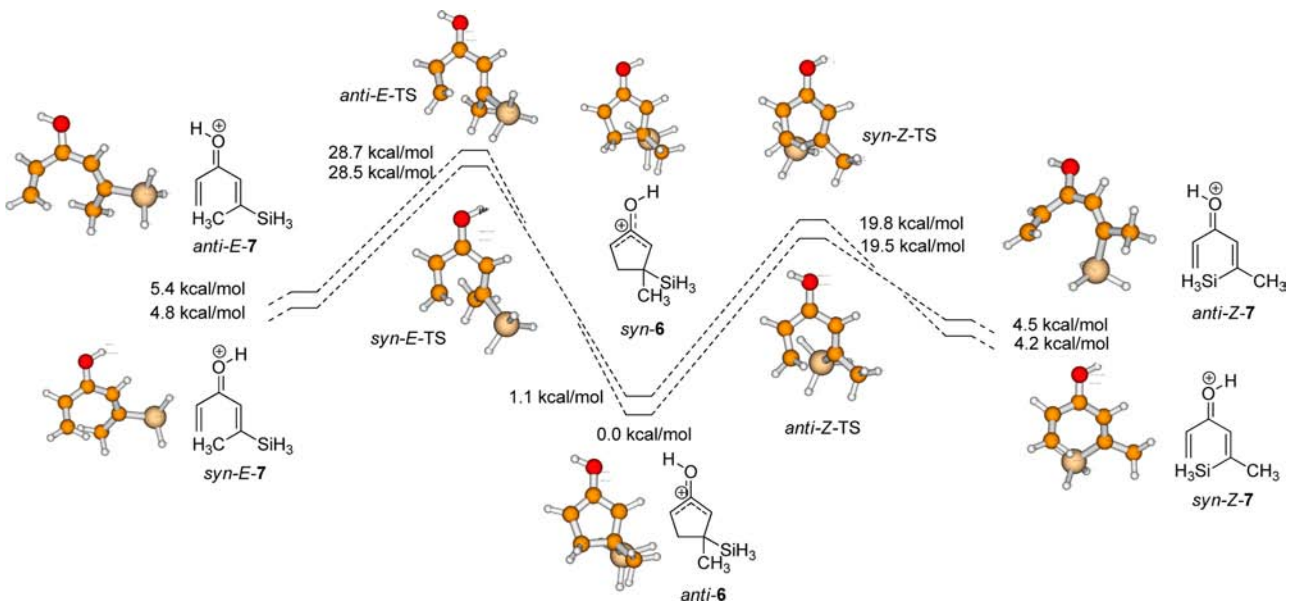


Figure 4. Reaction coordinates for the retro-Nazarov reactions of **6** (B3LYP/6-31G(d)).

rotation. For the relatively stable antiprotonated reactant *anti*-**6**, the enthalpy of activation for inward rotation was 9.2 kcal/mol (Figure 4). The syn-protonated isomer *syn*-**6** also prefers inward rotation of the silyl group.

Harmata et al.[12] calculated the retro-Nazarov reactions of 4-*tert*-butyl-4-methoxy-substituted cyclopentenone to show that the major product has the *tert*-butyl group at the *Z*-position despite the steric bulkiness. The geminal bond in this case is the C–C bond for the *tert*-butyl group, which has a higher σ_{CC} energy than the C–O bond for the methoxy group.

In conclusion, geminal bond participation, rather than vicinal bond participation, mainly controls torquoselectivity in the electrocyclic reaction. A geminal electron-donating σ-bond (σ-EDB) was shown to prefer inward rotation in retro-Nazarov reactions. The vicinal X–H bonds (X = B, C, O, Si, P, S) calculated here do not significantly act as acceptors toward cationic moieties. Vicinal bond participation cannot be expected to control the torquoselectivity of retro-Nazarov reactions.

Supporting Information Available. Theoretical calculation results. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.