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# Geminal bond participation in Alder ene reaction

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**Abstract**—We applied the geminal bond participation theory to Alder ene reactions. The interaction between the σ-orbital at the *Z*-position of the double bond of propene and the π*-orbital of ethylene was predicted to be bonding, while that at the *E*-position should be antibonding. This prediction was confirmed by the bond model analysis of the model compound. These results suggest that the reactivity could be enhanced by substituting a more electron-donating σ-bond at the *Z*-position. To examine our prediction, theoretical calculations were performed for the systematically substituted substrates. The prediction was confirmed except in the case where the inductive effect of oxygen could affect the reactivity. The same trend in reactivity was observed for formaldehyde as an enophile.

In previous studies, we suggested that geminal bond participation could be used to explain and predict the reactivity and selectivity in pericyclic reactions, including the Diels–Alder reaction,[1] Cope rearrangement,[2] sigmatropic [1,5]-hydrogen shifts,[3] the electrocyclic reaction,[4] and the cheletropic reaction.[5] The main issue in this theory involves the participation of the σ-bond of the reaction center (Fig. 1). We can divide the reactions into two types: (i) electron-donating σ-bond at the *Z*-position of the double bond enhances reactivity, and (ii) an electron-donating σ-bond rotates inwardly to occupy the *Z*-position. As examples of the former type, substitution of a more electron-donating σ-bond at the *Z*-position of the diene terminal enhances reactivity in the Diels–Alder reaction.[1] Lower activation enthalpies in Cope rearrangement[2] and sigmatropic [1,5]-hydrogen shifts[3] were calculated when the σ-bond at the *Z*-position was more electron donating. As examples of the latter type, preference for inward rotation of a more σ-bond electron-donating group was observed in the ring-opening reaction of cyclobutene[4] and the cheletropy reaction.[5]

These results originate from the bonding nature of the geminal bond participation of the σ-bond (Fig. 2). They are under the control of the phase continuity condition of the cyclic orbital interaction. Cyclic orbital interaction is required to meet the orbital phase continuity conditions:[6] (i) electron-donating orbitals are out of phase; (ii) the electron-donating orbital and the electron-accepting orbital are in phase; (iii) electron-accepting orbitals are in phase. When the geminal bonds are donors, the σ-orbitals of the geminal bonds and the vacant orbital a* do not satisfy the phase continuity requirement (Fig. 2). At the transition state, the delocalization from the inner σ-bond to the dienophile is bonding in the Diels–Alder reaction.[1] On the other hand, that from

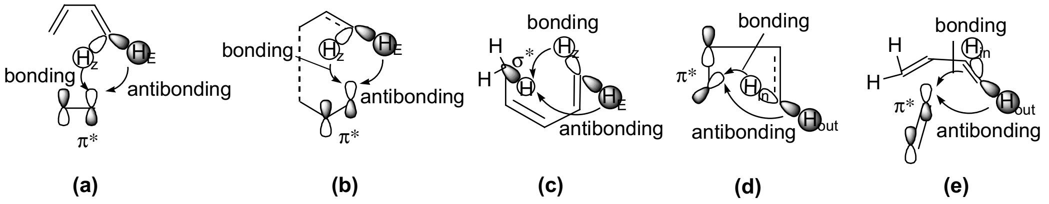

**Figure 1.** Geminal bond participation in (a) Diels–Alder reaction; (b) Cope rearrangement; (c) sigmatropic [1,5]-hydrogen shifts; (d) electrolytic reaction; (e) cheletropic reaction.

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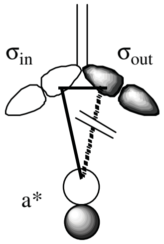
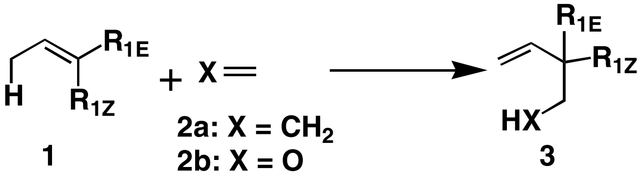


**Figure 2.** Orbital phase continuity condition of the geminal bond participation.

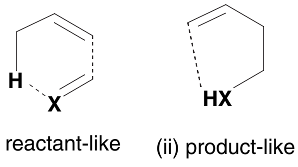
the outer σ-bond is antibonding. Delocalization from the *Z* σ-bond of the terminal olefin is bonding in Cope rearrangement, while the *E* σ-bond is antibonding.[2] The same trends were observed for the sigmatropic hydrogen shift[3] and electrocyclic reactions.[4] We examined our theory using a reaction of the latter type, i.e., torquoselectivity in cheletropic reactions, and the results were in good agreement with our theory.[5]

In this study, we examine the applicability of this theory to a reaction of the former type: the Alder ene reaction.[7,8] We report our theoretical analysis to show the general feature that essentially controls the reaction—reactivity and selectivity—in pericyclic reactions.



We now apply the geminal bond participation theory to Alder ene reactions. As a model reaction, we chose propene **1a** ($R_{1Z} = R_{1E} = H$) and ethylene **2a** ($X = CH_2$) to afford 4-pentene. Let us suppose that the bond connectivity at the transition state is reactant-like (i in Fig. 3), the same as in the pericyclic reactions we analyzed before. The delocalization from the *Z* σ-bond to the π*-orbital of the C=C bond should be bonding, while that from the *E* σ-bond should be antibonding. An electron-donating σ-bond at the *Z*-position would enhance reactivity.

We located the transition state[9] in the reaction of propene **1a** and ethylene **2a** at the RHF/6-31G* level[10] (Fig. 4), and subjected it to the bond model analysis.[11] To estimate the interactions between the bond orbitals, we used the interbond energy IBE.[12] In Alder ene reaction, an ene part is a donor and the enophile is an acceptor. In fact, the bond model analysis showed that the interactions of $\sigma_{C3\text{–}H6}$ with $\pi^*_{C1\text{–}C2}$ (IBE = −0.9329 a.u.), $\pi_{C1\text{–}C2}$ with $\pi^*_{C4\text{–}C5}$ (IBE = −0.8599 a.u.) and $\pi_{C4\text{–}C5}$ with $\sigma^*_{C3\text{–}H6}$ (IBE = −0.7892 a.u.) are the most important (Table 1). The reverse interactions of $\pi_{C1\text{–}C2}$ with $\sigma^*_{C3\text{–}H6}$, $\pi_{C4\text{–}C5}$ with $\pi^*_{C1\text{–}C2}$ and $\sigma_{C3\text{–}H6}$ with $\pi^*_{C4\text{–}C5}$ are not so effective. For geminal bond participation, the delocalization from the geminal σ-bond to the π*-orbital of the C=C bond of the enophile should play a more essential role because the enophile is an acceptor. In fact, the delocalization from the σ-bond at the *Z*-position to the π*-orbital of the C=C bond shows bonding character (IBE($\sigma_{C1\text{–}HZ}, \pi^*_{C4\text{–}C5}$) = −0.0182 a.u.), while that from the *E*-position is antibonding (IBE($\sigma_{C1\text{–}HE}$, $\pi^*_{C4\text{–}C5}$) = 0.0040 a.u.) (Fig. 5). These results are in good agreement with our prediction.



(i) reactant-like (ii) product-like

**Figure 3.** The bond models for the transition state of the ene reaction.

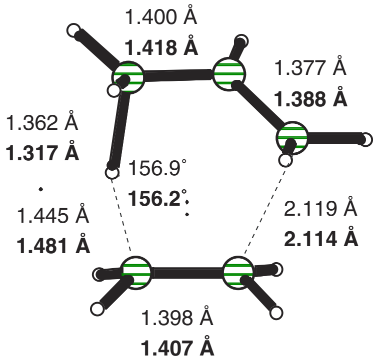


**Figure 4.** Transition structure of the Alder ene reaction of propene and ethylene (RHF/6-31G* and B3LYP/6-31G* in bold).

**Table 1.** The bond interactions at the transition state (RHF/6-31G*)

| Bond interaction | IBE/a.u. |
|---|---|
| $\sigma_{C3\text{–}H6}\text{–}\pi^*_{C1\text{–}C2}$ | −0.9329 |
| $\pi_{C1\text{–}C2}\text{–}\sigma^*_{C3\text{–}H6}$ | −0.2052 |
| $\pi_{C1\text{–}C2}\text{–}\pi^*_{C4\text{–}C5}$ | −0.8599 |
| $\pi_{C4\text{–}C5}\text{–}\pi^*_{C1\text{–}C2}$ | −0.1153 |
| $\pi_{C3\text{–}H6}\text{–}\pi^*_{C4\text{–}C5}$ | −0.6224 |
| $\pi_{C4\text{–}C5}\text{–}\sigma^*_{C3\text{–}H6}$ | −0.7892 |
| $\sigma_{C1\text{–}HZ}\text{–}\pi^*_{C4\text{–}C5}$ | **−0.0182** |
| $\sigma_{C1\text{–}HE}\text{–}\pi^*_{C4\text{–}C5}$ | **0.0040** |
| $\pi_{C4\text{–}C5}\text{–}\sigma^*_{C1\text{–}HZ}$ | −0.0035 |
| $\pi_{C4\text{–}C5}\text{–}\sigma^*_{C1\text{–}HE}$ | 0.0047 |

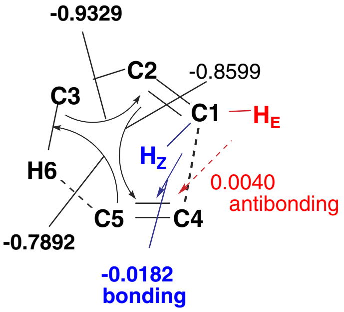


**Figure 5.** The interbond energies (IBE/a.u.) at the transition state of the ene reaction **1a**.

**Table 2.** Calculated activation enthalpies (B3LYP/6-31G*, ZPE corrected)

| Substrate | $\Delta H^{\ddagger}$/kcal mol$^{-1}$ | Substrate | $\Delta H^{\ddagger}$/kcal mol$^{-1}$ | $\Delta H^{\ddagger}$ |
|---|---|---|---|---|
| **1bE** ($R_{1Z} = CH_3$, $R_{1E} = H$) | **35.7** | **1bZ** ($R_{1Z} = H$, $R_{1E} = CH_3$) | **34.5** | **1.2** |
| **1cE** ($R_{1Z} = NH_2$, $R_{1E} = H$) | **37.0** | **1cZ** ($R_{1Z} = H$, $R_{1E} = NH_2$) | **35.4** | **1.6** |
| **1dE** ($R_{1Z} = OH$, $R_{1E} = H$) | **36.2** | **1dZ** ($R_{1Z} = H$, $R_{1E} = OH$) | **35.3** | **0.9** |
| **1eE** ($R_{1Z} = CH_3$, $R_{1E} = SiH_3$) | **37.1** | **1eZ** ($R_{1Z} = SiH_3$, $R_{1E} = CH_3$) | **36.0** | **1.1** |
| **1fE** ($R_{1Z} = NH_2$, $R_{1E} = PH_2$) | **38.3** | **1fZ** ($R_{1Z} = PH_2$, $R_{1E} = NH_2$) | **36.8** | **1.5** |
| **1gE** ($R_{1Z} = OH$, $R_{1E} = SH$) | **36.5** | **1gZ** ($R_{1Z} = SH$, $R_{1E} = OH$) | **35.5** | **1.0** |

We can now predict that a more electron-donating σ-bond substituent at the *Z*-position of the C1 atom should enhance the reactivity. To test our prediction, we calculated the transition state of the reactions of systematically substituted **1b–g**. The electronegativity of Si atom (1.9) is less than that of carbon (2.6). Within the same group, a σ-bond with a heavier atom should be more electron donating. Thus, the silyl group should be placed at the *Z*-position to enhance the reactivity in **1e**. In fact, the *Z*-isomer **1eZ** ($\Delta H^{\ddagger} = 36.0$ kcal/mol) is more reactive than the *E*-isomer **1eE** ($\Delta H^{\ddagger} = 37.1$ kcal/mol) at the B3LYP/6-31G* level.

The transition states of the reactions of **1e** were subjected to the bond model analysis. For the *Z*-isomer **1eZ**, the interaction between the C–Si σ-bond at the *Z*-position and $\pi^{\bullet}_{C=C}$ (enophile) shows bonding ($\mathrm{IBE}(\sigma_{C\text{–}Si/Z}, \pi^{\bullet}_{C=C}) = -0.0704$ a.u.), while that between the C–C σ-bond at the *E*-position and $\pi^{\bullet}_{C=C}$ (enophile) is antibonding ($\mathrm{IBE}(\sigma_{C\text{–}C/E}, \pi^{\bullet}_{C=C}) = 0.0332$ a.u.). For the *E*-isomer **1eE**, however, the σ-bond (C–Si) at the *E*-position is more electron donating than that (C–C) at the *Z*-position. The C–Si bond at the *E*-position shows the bonding character in the interaction with $\pi^{\bullet}_{C=C}$ (enophile) ($\mathrm{IBE}(\sigma_{C\text{–}Si/E}, \pi^{\bullet}_{C=C}) = -0.0054$ a.u.) though it is weak due to unfavorable geometrical situation of the *E*-position. The delocalization from the C–C σ-bond at the *Z*-position is a little antibonding ($\mathrm{IBE}(\sigma_{C\text{–}C/Z}, \pi^{\bullet}_{C=C}) = 0.0003$ a.u.) (Fig. 6).

In an analogous fashion, the phosphino and mercapto groups should occupy the *Z*-position in **1f** and **1g**, respectively, to enhance the reactivity. The results of B3LYP/6-31G* calculations are summarized in Table 2 together with those of the other substituents, which are in agreement with our prediction. We expected that a greater difference in electronegativity ($\Delta EN = 0.7$ for C–Si; 0.9 for N–P; 1.0 for O–S) would lead to a greater difference in reactivity. However, a smaller difference in reactivity was obtained with **1g** than with **1e** and **1f**. We assume that this result might come from the inductive effect of oxygen, the same as in other pericyclic reactions.[1–5]

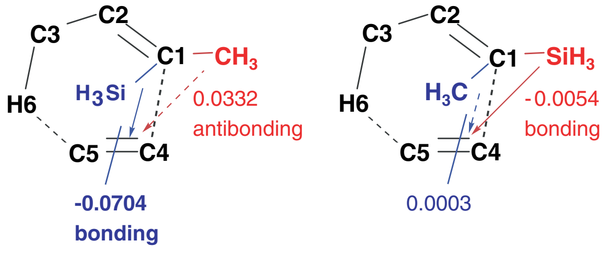


**Figure 6.** The interbond energies (IBE/a.u.) at the transition states of the ene reaction of **1eZ** and **1eE**.

We further investigated Alder ene reactions with formaldehyde **2b** as the enophile (Prins reaction). We located the transition structure at RHF/6-31G* (Fig. 7) and subjected it to the bond model analysis. The carbonyl group

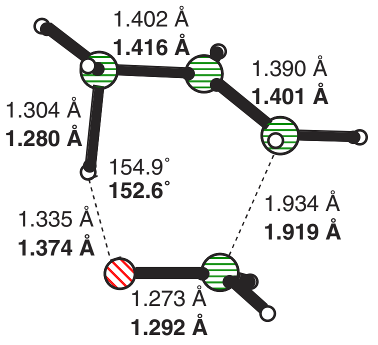


**Figure 7.** Transition structure of the ene reaction of propene and formaldehyde (RHF/6-31G*; B3LYP/6-31G* in bold).

**Table 3.** The bond interactions at the transition state (RHF/6-31G*)

| Bond interaction | IBE/a.u. |
|---|---|
| $\sigma_{C3\text{–}H6}\text{–}\pi^{*}_{C1\text{–}C2}$ | −1.3192 |
| $\pi_{C1\text{–}C2}\text{–}\sigma^{*}_{C3\text{–}H6}$ | 0.0250 |
| $\pi_{C1\text{–}C2}\text{–}\pi^{*}_{C4\text{–}O5}$ | −2.0739 |
| $\pi_{C4\text{–}O5}\text{–}\pi^{*}_{C1\text{–}C2}$ | 0.0021 |
| $\sigma_{C3\text{–}H6}\text{–}\pi^{*}_{C4\text{–}O5}$ | −0.1436 |
| $\pi_{C4\text{–}O5}\text{–}\sigma^{*}_{C3\text{–}H6}$ | −0.5157 |
| $\sigma_{C1\text{–}HZ}\text{–}\pi^{*}_{C4\text{–}O5}$ | **−0.0139** |
| $\sigma_{C1\text{–}HE}\text{–}\pi^{*}_{C4\text{–}O5}$ | **0.0318** |
| $\pi_{C4\text{–}O5}\text{–}\sigma^{*}_{C1\text{–}HZ}$ | −0.0022 |
| $\pi_{C4\text{–}O5}\text{–}\sigma^{*}_{C1\text{–}HE}$ | 0.0191 |
| $n_{O5}\text{–}\sigma^{*}_{C3\text{–}H6}$ | −0.4844 |
|  | −0.0562 |

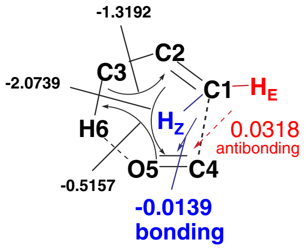


**Figure 8.** The interbond energies (IBE/a.u.) at the transition state of the ene reaction of **1a**.

**Table 4.** Calculated activation enthalpies (B3LYP/6-31G*, ZPE corrected)

| Substrate | $\Delta H^{\ddagger}$/kcal mol$^{-1}$ | Substrate | $\Delta H^{\ddagger}$/kcal mol$^{-1}$ | $\Delta H^{\ddagger}$ |
|---|---|---|---|---|
| **1bE** ($R_{1Z} = CH_3$, $R_{1E} = H$) | **28.4** | **1bZ** ($R_{1Z} = H$, $R_{1E} = CH_3$) | **28.0** | **0.4** |
| **1cE** ($R_{1Z} = NH_2$, $R_{1E} = H$) | **30.5** | **1cZ** ($R_{1Z} = H$, $R_{1E} = NH_2$) | **30.0** | **0.5** |
| **1dE** ($R_{1Z} = OH$, $R_{1E} = H$) | **29.5** | **1dZ** ($R_{1Z} = H$, $R_{1E} = OH$) | **30.5** | **−1.0** |
| **1eE** ($R_{1Z} = CH_3$, $R_{1E} = SiH_3$) | **30.6** | **1eZ** ($R_{1Z} = SiH_3$, $R_{1E} = CH_3$) | **29.8** | **0.8** |
| **1fE** ($R_{1Z} = NH_2$, $R_{1E} = PH_2$) | **32.6** | **1fZ** ($R_{1Z} = PH_2$, $R_{1E} = NH_2$) | **32.4** | **0.2** |
| **1gE** ($R_{1Z} = OH$, $R_{1E} = SH$) | **31.5** | **1gZ** ($R_{1Z} = SH$, $R_{1E} = OH$) | **31.3** | **0.2** |

is a better acceptor. Compared to the reaction with ethylene, the orbital interactions between $\pi_{C1-C2}$ and $\pi^*_{C4-O5}$ (IBE = −2.0739 a.u.) and between $\sigma_{C3-H6}$ and $\pi^*_{C1-C2}$ (IBE = −1.3192 a.u.) are enhanced, while less stabilization results for the interaction between $\pi_{C4-O5}$ and $\sigma^*_{C3-H6}$ (IBE = −0.5157 a.u.) (Fig. 8). For the geminal bond participation, the same trend was observed. Delocalization from the inner $Z$ σ-bond to $\pi^*_{C4-O5}$ is bonding (IBE = −0.0139 a.u.), while the one from the $E$ σ-bond is antibonding (IBE = 0.0318 a.u.). These results are summarized in Table 3.

We also calculated the reactions of systematically substituted substrates at the B3LYP/6-31G* level and found the results in accordance with our prediction except with **1dE** as the substrate, which might be affected by the inductive effect (Table 4).

We have demonstrated here that *the geminal bond participation is general* for pericyclic reactions. The further application of this theory to other reactions is currently underway in our laboratory.

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