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<th>The charge-transfer interaction and successive thermal (2+2) cycloaddition of α, β-unsaturated ethers with tetracyanoethylene</th>
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<tr>
<td>Author(s)</td>
<td>Arimoto, Tateo; Osugi, Jiro</td>
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THE CHARGE-TRANSFER INTERACTION AND SUCCESSIVE THERMAL 
(2 + 2) CYCLOADDITION OF α, β-UNSATURATED ETHERS WITH 
TETRACYANOETHYLENE

BY TATEO ARIMOTO and JIRO OSUGI

The systems of α, β-unsaturated ethers and substituted olefins with tetra-
cyanoethylene (TCNE) give deeply colored 1 : 1 CT complexes immediately after 
mixing. Subsequently, the complexes react to form colorless 1, 1, 2, 2-tetra-
cyano-1-cyclobutanes only in the case of the ethers. Equilibrium studies on the complex 
formations and kinetic studies on the successive thermal (2 + 2) cycloaddition 
reactions were made in such poor solvents as CH₂Cl₂, CHCl₃ and CCl₄ in the 
temperature range 10-40°C by the spectrophotometric method.

TCNE-unsaturated ether and TCNE-olefin complexes exhibit gradual in-
creases in stability with the increase of the double-bond substitution, in contrast 
with Ag⁺-unsaturated ether, Ag⁺-olefin and I₂-olefin complexes where the com-
plexes become more unstable with increasing substitution at the double bond.
This tendency could be interpreted by considering that the electronic and steric 
effects of the substituents are mutually competing. Furthermore, there is signifi-
cant difference in the substituent effect on the reactivity between the complex 
formation and the successive cycloaddition. The difference would be caused by 
the fact that the steric effect is more important in the activation process of the 
cycloaddition because the transition state seems much more rigid than the com-
pound state. The cycloaddition reaction proceeds stereoselectively.

The experimental results were discussed on the basis of the extended 
Hückel molecular orbital (EHMO) theory and the molecular orbital correlation 
diagram.

**Introduction**

Since the end of the 19th century it had been known to chemists that two molecules with their 
valencies saturated interact to form a stable complex. Various theoretical speculations had been pro-
posed for interpreting this phenomenon, until about 20 years ago Mulliken\(^1\) achieved real insight into 
the molecular nature of some type of the complex on the basis of quantum mechanics; Mulliken's 
theory is called "Charge-Transfer (CT) Theory". Since then the information on the thermodynamic 
behaviors of CT complexes have increased\(^2\). However, the practical role of CT complexes in the 
reaction has been carefully examined only in a few instances\(^3\). even though such complexes as

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(Received March 26, 1974)

   Francisco (1964)
Dewar’s π-complex⁵ and Wheland’s σ-complex⁷ are frequently postulated as intermediates or transition states.

Recently Williams et al.⁸ found that TCNE cycloadds thermally to electron-rich olefins under mild conditions, but its mechanism has not been examined. For this purpose we studied the reactions of α, β-unsaturated ether and substituted olefin with TCNE⁹,¹⁰, which are thought to be the good models for investigating the possible role of CT complexes. These systems are so simple that the substituents on the double bond have considerably large effects on the NMR spectra, on the CT bands, and on the relative reactivities both in the complex formation and in the cycloaddition. The following two basic problems are discussed in this paper. First, how do the substituents affect the energy level and the electron distribution of the donor; practically its ionization potential and NMR spectrum? Secondly, how do the energy level and the electron distribution determine the reactivities both in the complex formation and in the successive reaction?

![Fig. 1 α, β-unsaturated ether](image)

**Experimental**

**Materials**

Propenyl ethyl ether (PEE), isobutenyl ethyl ether (IBEE), 1,2-diethoxyethylene, and p-methoxystyrene were prepared by the known methods. The other donor was commercially available. All the donors were purified by the method described elsewhere. TCNE was recrystallized from chlorobenzene three times, and then sublimed under high vacuum. The sublimate was colorless and its melting point was 200-202°C. Spectrograde CCl₄ was used without further purification. CH₂Cl₂ and CHCl₃ were purified by the usual method.

**Apparatus and Procedure**

Ultraviolet-visible spectra were measured with a Shimazu UV-200 and a Hitachi EPU-2A spectrophotometer. Thermostated water was circulated around the quartz observation-cell compartment (optical
Charge-Transfer Interaction and Successive Thermal (2+2) Cycloaddition of α, β-Unsaturated Ethers

path length is 10 mm) and the donor and acceptor solution reservoirs; the temperature was regulated within ±0.2°C. The donor and acceptor solutions were mixed directly in the observation cell. The initial absorption measurements could be made within 6 sec. All kinetic and equilibrium experiments were carried out with the donor in large excess over the acceptor; the donor concentration, \((D) = 0.2 - 1.6 \text{ M}\) and the acceptor concentration, \((A) = \text{ca.} 10^{-3} \text{ M}\). The cycloaddition reaction was followed by observing the CT band maximum and, if necessary, various wave lengths near this. The pseudo first order rate constant was obtained by Guggenheim’s plot. The initial association constant was obtained by Benesi-Hildebrand (B-H) plot\(^{10}\). In the case of reacting systems, we made use of the absorbance value obtained from the extrapolation of Guggenheim’s plot to zero time in order to take the B-H plot.

NMR spectra were taken at 100 MHz using deuterioacetone and CCl\(_4\) as solvents with TMS as an internal reference at room temperature.

Results and Discussion

Assignment of the new band

The maximum of the observed new band and H\(_C\) chemical shift of the donor are listed in Table 1. We can see that the effects of β-substituents are much larger than those of α-substituents on these

<table>
<thead>
<tr>
<th>REACTIVE(^{13})</th>
<th>Donor</th>
<th>(\lambda_{CT})</th>
<th>(\tau) value of H(_C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vinyl 2-chloroethyl ether (V2-CIEE)</td>
<td>403 nm</td>
<td>3.64 ppm</td>
<td></td>
</tr>
<tr>
<td>vinyl methyl ether (VME)</td>
<td>410</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>vinyl ethyl ether (VEE)</td>
<td>428</td>
<td>3.70</td>
<td></td>
</tr>
<tr>
<td>vinyl n-butyl ether (Vn-BE)</td>
<td>432</td>
<td>3.72</td>
<td></td>
</tr>
<tr>
<td>vinyl isobutyl ether (Vi-BE)</td>
<td>436</td>
<td>3.74</td>
<td></td>
</tr>
<tr>
<td>cis-propenyl ethyl ether (cis-PEE)</td>
<td>480</td>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td>trans-propenyl ethyl ether (trans-PEE)</td>
<td>480</td>
<td>3.90</td>
<td></td>
</tr>
<tr>
<td>isobutenyl ethyl ether (IBEE)</td>
<td>518</td>
<td>4.42</td>
<td></td>
</tr>
<tr>
<td>2,3-dihydro pyran</td>
<td>471</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,2-diehoxo ethylene</td>
<td>582</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p-methoxystyrene</td>
<td>586</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NONREACTIVE(^{13})</th>
<th>Donor</th>
<th>(\lambda_{CT})</th>
<th>(\tau) value of H(_C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pentene-1</td>
<td>340</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>pentene-2</td>
<td>404</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>2-methyl-2-butene</td>
<td>467</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td>tetramethylethylene</td>
<td>562</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cyclohexene</td>
<td>420</td>
<td></td>
<td></td>
</tr>
<tr>
<td>styrene</td>
<td>475</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(\text{a)}\) “REACTIVE” indicates that the cycloadducts could be identified by the product analyses (IR, UV, NMR and elemental analysis).

\(\text{b)}\) “NONREACTIVE” indicates that the cycloadducts could not be identified.

spectra. The new band is assigned to the CT absorption band from the following reasons. First, as Mulliken's CT theory predicts, the plot of the frequencies of the new bands against the experimental ionization potentials of the donors really shows a linear relationship in Fig. 2. Then, the complex stoichiometry is found 1 : 1 from the continuous variation plot. Furthermore, the 'H-NMR chemical shift of H and OCH in the complexed IBEE is about 0.1 ppm to the lower field in comparison with the isolated IBEE in CCl, and the other protons do not show any shift; these shifts probably suggest that partial charge would migrate from the donor to the acceptor. According to these results, it can be concluded that the appearance of the new band is due to the formation of 1 : 1 CT complex.

Complex formation equilibrium

The equilibrium constant of the complex formation, K and molar extinction coefficient, ε were determined by B–H plot as seen in Fig. 3. The values of ε do not vary among the donors used: 2000 ± 50 in CHCl and 1400 ± 100 in CCl. The heat and entropy of formation (ΔH° and ΔS°) are determined from the temperature dependence of K value, assuming ε has no temperature dependence, and using the equation R ln K = -ΔH°(1/T) + ΔS° R ln ε. The thermodynamic parameters obtained thus are listed in Table 2. The values of ΔH° and ΔS° are both negative and have magnitudes similar to those of common π-π complexes.

It is found that there are good linear relationships between the obtained values of log K and εCT, and lines A and B have the same slope as seen in Fig. 4. According to Mulliken's simplified resonance theory, the wave function for the ground state (N) of a complex is generally expressed as Eq. (1).
Table 2  The thermodynamic parameters for the TCNE complex formation equilibria

<table>
<thead>
<tr>
<th>Donor</th>
<th>10°C</th>
<th>20°C</th>
<th>30°C</th>
<th>40°C</th>
<th>(\Delta H^\circ) (kcal mol(^{-1}))</th>
<th>(\Delta S^\circ) (e. u.)</th>
<th>Solvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBEE</td>
<td>2.16</td>
<td>1.91</td>
<td>1.34</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>CHCl(_3)</td>
</tr>
<tr>
<td>cis-PEE(^{a})</td>
<td>0.74</td>
<td>0.65</td>
<td>0.52</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>CHCl(_3)</td>
</tr>
<tr>
<td>trans-60-PEE(^{b})</td>
<td>0.24</td>
<td>0.21</td>
<td>0.18</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>CHCl(_3)</td>
</tr>
<tr>
<td>styrene</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>CHCl(_3)</td>
</tr>
<tr>
<td>p-methoxystyrene</td>
<td>--</td>
<td>0.93</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>CHCl(_3)</td>
</tr>
<tr>
<td>p-methoxystyrene</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>CHCl(_3)</td>
</tr>
</tbody>
</table>

a) 95 vol. \% CHCl\(_3\)-5 vol. \% CH\(_2\)Cl\(_2\)
b) and c) cis-PEE indicates the PEE containing 95\% cis isomer and trans-60-PEE indicates the PEE containing 60\% trans isomer, because the geometrical isomers of PEE could not be completely separated.

Fig. 4  A plot of log \(K\) vs. the frequency of the CT band for some TCNE complexes

- A: TCNE at 30°C in CHCl\(_3\)
- B: TCNE at 20°C in CHCl\(_3\)
- C: I\(_2\) at 23°C in isooctane
- D: Ag\(^+\) at 20°C in ethylene glycol

1; V2-CIEE  2; VME  3; VEE
4; Vi-BE  5; Vn-BE  6; cis-PEE
7; IBEE  8; styrene
9; p-methoxystyrene

Fig. 5  Charge-transfer interaction diagram

The energy of formation \(\Delta W\) can be approximately written from Eqs. (2) and (3) as: 

\[
\psi_N = a \psi_0 (D, A) + b \psi_0 (D^+ - A^-) 
\]

\[
W_N \approx W_0 - \frac{|H_{01} - S_{01} W_0|^2}{W_1 - W_0} 
\]

\[
\frac{b}{a} \approx \frac{H_{01} - S_{01} W_0}{W_1 - W_0} 
\]

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\[ dW = - \left( \frac{b}{a} \right)^2 (W_1 - W_0). \]  

(4)

Here, \( W_1 - W_0 \) is approximately equal to the CT transition energy \( \hbar \nu_{\text{CT}} \). Then, we have

\[ dW \approx - \left( \frac{b}{a} \right)^2 \hbar \nu_{\text{CT}}. \]  

(5)

When the donor molecules differ little in polarity, size, and polarizability with the acceptor fixed, the contribution of the conventional van der Waals force to the complex formation would not vary so much in the series. If so, the relative variation in \( dW \) by the substituent can be expressed as:

\[ \frac{\partial dW}{dW^*} = - \left( \frac{b}{a} \right)^2 \hbar (\nu_{\text{CT}} - \nu_{\text{CT}}^*). \]  

(6)

where the superscript "*" indicates a reference compound. In the case of weak CT complexes the value of \( \left( \frac{b}{a} \right)^2 \) is almost constant in the series. Then, we have

\[ \frac{\partial dW}{dW^*} \approx - \left( \frac{b^*}{a^*} \right)^2 \hbar (\nu_{\text{CT}} - \nu_{\text{CT}}^*). \]  

(7)

When we make the usual assumption that the variation in the equilibrium constant, \( K \), is mainly due to the change in the energy rather than due to the change in the entropy of formation, after all, we have from Eq. (7)

\[ \ln \frac{K}{K^*} \approx \frac{1}{RT} \left( \frac{b^*}{a^*} \right)^2 \hbar (\nu_{\text{CT}} - \nu_{\text{CT}}^*). \]  

(8)

The fact that Eq. (8) is obeyed reasonably well in TCNE-ether complexes as seen in Fig. 4 does suggest that the variation in the value of \( K \) is almost due to that in the CT resonance energy\(^{(16)}\). The line C in Fig. 4 shows a similar relationship in molecular iodine (I\(_2\))-alkyl vinyl ether complexes\(^{(17)}\). By the gradient of this line the value of \( b^2 \) can be estimated from Eq. (8): it is about 0.04 \( a^2 \) for TCNE-ether complexes and about 0.08 \( a^2 \) for I\(_2\)-alkyl vinyl ether complexes. The obtained values of \( b^2 \) are in good agreement with those determined for some other CT complexes by IR or dipole moment measurement\(^{(12,13)}\).

However, in the case of Ag\(^+\)-unsaturated ether complexes\(^{(18)}\) the plot of \( \log K \) vs. \( \nu_{\text{CT}} \) has an inverse tendency, which would mean that the effect of \( \beta\)-methyl groups on the stability of Ag\(^+\) complexes is negative on the contrary to that of TCNE complexes. This tendency could be interpreted by considering that the interaction distance between the donor and acceptor is much smaller than the sum of their van der Waals radii so that the steric hindrance of the \( \beta\)-methyl group may become important. In general the donor-acceptor distance in \( \pi-\pi \) complexes appears to be only slightly shorter than the sum of their van der Waals radii, while it is considerably shorter than that in the case of \( \gamma\)-acceptor, Ag\(^+\) complexes and \( \sigma\)-acceptor, I\(_2\) complexes. In addition, a similar phenomenon is observed in another case: the TCNE-olefin complexes studied here exhibit gradual increases in stability with increasing the double-bond substitution, in contrast with Ag\(^+\)-olefin and I\(_2\)-olefin complexes\(^{(19)}\) which become more unstable with

\(\begin{align*}
\end{align*}\)
the increase of substitution at the double bond.

It is found that the higher the NMR chemical shift of H$_D$ in the corresponding donor, the larger the stability of the TCNE complex. Really, there are linear relationships between log$K$ and $\tau$ value of H$_D$ as seen in Fig. 6. The $^{13}$C-NMR spectra reported by other authors$^{20}$, $^1$H-NMR spectra and the

![Fig. 6 A plot of log$K$ vs. H$_D$ chemical shift](image)

EHMO calculation described below show that $\pi$-electron density on the $\alpha$-carbon (C$_a$) increases and that on C$_\beta$ decreases as alkoxy groups become bulkier and the number of $\beta$-substituents increases. According to these facts, it could be supposed that the interaction of $\pi$-electron on C$_a$ with TCNE is more important than the interaction of $\pi$-electron of C$_\beta$ with TCNE in the complex formation.

**Extended Huckel MO calculation**

**Method of calculation**

As previously discussed the steric effect is less important in the initial complex formation. Thus the relative reactivity in the complex formation could be discussed mainly in terms of the electronic energy change between the initial stage and the complex stage. Such energy change may be approximately estimated by a MO method. In order to consider the effects of $\alpha$- and $\beta$-substituents, $\sigma$-electronic system should be dealt with as well as $\pi$-system, and then the EHMO method developed by Hoffmann$^{20}$ was adopted here. All the calculations and parametrizations were performed according to the original prescription of Hoffmann. Since the geometry of each molecule except TCNE$^{20}$ has not been established, a resonable one was postulated with the usual bond lengths and angles$^{22}$, although the C-O-C bond angle was arbitrarily assumed to be tetrahedral. The molecular geometry adopted

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   (b) R. J. Cvetanović, F. J. Duncan, W. E. Falconer and W. A. Sunder, *ibid.*, 88, 1602 (1966)
here for VEE is shown in Fig. 7.

\[ \text{Fig. 7 The molecular geometry adopted here for VEE} \]

The numerical value in the parenthesis is the calculated total electronic energy.

Comparison with experiments

The electron population data given in Table 3 suggest that the electrophilic reactivity at \( C_\beta \) is reduced and, on the other hand, that at \( C_\alpha \) is increased by the \( \beta \)-methyl substitutions. In fact, these population data on \( C_\alpha \) coincide well with our experimental reactivity order for the complex formation: VEE<trans-PEE<cis-PEE<IBEE. This result supports the previous assumption that the role of \( \pi \)-electron on \( C_\alpha \) is more significant than that on \( C_\beta \) in the complex. However, the total atomic population (AP) on \( C_\beta \) is far greater than that on \( C_\alpha \) in contrast with the \( \pi \)-atomic orbital population (\( \pi \)-AOP) and the highest occupied \( \pi \)-atomic orbital population (HO, \( \pi \)-AOP). As \( \pi \)-electron certainly plays a dominant role in such \( \pi \)-\( \pi \) complexes, the \( \pi \)-AOP or HO, \( \pi \)-AOP would be one of the best reactivity indices for the complex formation. From the viewpoint, however, we cannot examine the configuration of the complex. For this purpose it is a better method to estimate the delocalization energy for various kinds of configuration models shown in Fig. 8. The \( \pi \)-electronic delocalization energy for model (C) (\( \Delta E_C \)) is approximately given by Eq. (9).

\[ \Delta E_C = 2 \sum \frac{n_{\pi}}{T} \left( \sum \frac{n_{\pi}}{T} \right) \left( \frac{C_{\pi}C_{\pi}I_{\pi} + C_{\pi}C_{\pi}I_{\pi}}{E_i - E_j} \right) (-\gamma^2) \]

where \( \gamma \) is the resonance integral between the component molecules being assumed for simplicity to be constant for any type of interaction. The values of \( \Delta E \) for various configuration models are summarized in Table 4. Models (B), (C) and (E) adequately predict our experimental results. Among these three models, model (E) is in most reasonable agreement with Mulliken's "Overlap and orientation principle"\(^{20}\).

\[ ^{20} \text{R. S. Mulliken, Rec. Trav. Chim., 75, 845 (1956)} \]
Before the kinetic experiments were carried out, we thought that this model was regarded as a good transition state model for the cycloaddition, and that the delocalization energy was an index of the activation energy. As discussed below, however, the steric effect is important to some degree in the process of the cycloaddition, and it is concluded that the reactivity indexes derived from the EHMO method in which only the electronic energy change is considered cannot be applied to the successive cycloaddition.

**Kinetics**

A characteristic color due to the 1:1 CT complex appears immediately after mixing and gradually diminishes; during the change of the color, in NMR spectra only the reactant ether and the cycloadduct are observed and nothing else can be found. Just at the time the color completely disappears, the change in the NMR spectra stops. In this reaction process TCNE anion radical could not be detected[20]. Thus the cycloaddition accompanies no side reactions. The cycloaddition was followed by observing the CT band and the pseudo first order rate constant obtained by Guggenheim's plot was almost constant despite the different wave lengths near the CT maximum band. The second order rate constant, \( k_{II} \), is pseudo first order rate constant divided by the initial donor concentration \( (D) \); first order in the donor and in the CT complex respectively. The value of \( k_{II} \) decreases with the increase in \( (D) \) for

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cis-PEE and IBEE, while it is independent of \((D)\) for VEE, Vi-IBE, VME and V2-CIEE within the experimental error. Dependence of \(k_{11}\) on the acceptor concentration is not found for all the systems in the concentration range from \(7.0 \times 10^{-4}\) M to \(3.5 \times 10^{-3}\) M. Those phenomena can be satisfactorily interpreted by Scheme (1) or (2), though Rappoport et al.\(^{26}\) proposed Scheme (3) based on the similar kinetic study in the tricyanovinylation of aromatic amines. Schemes (1) and (2) predict the decrease of \(k_{11}\) with the increase in \((D)\) for cis-PEE and IBEE. On the other hand, in the case of Scheme (3) the increase in \((D)\) must increase the value of \(k_{11}\) unless \(K(D) > 1\); however \(K(D)\) is not so larger than 1 for our systems. The value of \(k_{11}\) is independent of \((D)\) for VEE etc. because \(K(D) < 1\) in Eq. (1-2) or (2-2), and then \(k_{11} = k_{r} K\) or \(k_{r}'\), respectively. As discussed extensively by Andrews and Seeter\(^{26}\), however, the kinetic method alone does not enable us to distinguish between Scheme (1) in which the complex lies on the reaction co-ordinate and Scheme (2) in which the complex formation is a side reaction in a rapid equilibrium with free donor and acceptor. As expected from Eq. (1-3) or (2-3), the plot of \(1/k_{11}\) vs. \((D)\) has fairly good linearity for cis-PEE and IBEE as seen in Fig. 9. The rate constants \(k_{r}, k_{r}'\), and initial association constant \(K\) are determined by the slope and intercept of the plot. The value of \(K\) obtained thus is found in good accordance with that previously determined by the B-H plot. The obtained kinetic parameters for both Schemes (1) and (2) are listed in Table 5.

As seen in the interesting plots of \(\log k_{r}\) and \(k_{r}'\) against \(v_{CT}\) in Fig. 10, each curve is not linear with a shallow minimum in contrast with that of the complex formation (Fig. 4). There is an essential difference in the substituent dependence on the relative reactivity between in the cycloaddition and in the CT complex formation. Thus, the reactivity difference between the cycloaddition and the complex

\[\text{Scheme (1)}\]
\[
A + D \xrightarrow{K} C \xrightarrow{k_{r}} P
\]
\[
\frac{\text{d}(C)}{\text{dt}} = -\frac{k_{r} K(D)(C)}{1 + K(D)}
\]
\[
k_{1} = \frac{k_{r} K}{1 + K(D)}
\]
\[
\frac{1}{k_{1}} = \frac{1}{k_{r}} + \frac{1}{K(D)}
\]

\[\text{Scheme (2)}\]
\[
C \xrightarrow{K} A + D \xrightarrow{k_{r}'} P\]
\[
\frac{\text{d}(C)}{\text{dt}} = -\frac{k_{r}'(D)(C)}{1 + K(D)}
\]
\[
k_{1} = \frac{k_{r}' K(D)}{1 + K(D)}
\]
\[
\frac{1}{k_{1}} = \frac{1}{k_{r}'} + \frac{1}{K(D)}
\]

\[\text{Scheme (3)}\]
\[
A + D \xrightarrow{K} C \xrightarrow{k_{r}'} P + D
\]
\[
\frac{\text{d}(C)}{\text{dt}} = -\frac{k_{r}' K(D)(C)}{1 + K(D)}
\]
\[
k_{1} = \frac{k_{r}' K(D)}{1 + K(D)}
\]
\[
\frac{1}{k_{1}} = \frac{1}{k_{r}'} + \frac{1}{K(D)}
\]
Charge-Transfer Interaction and Successive Thermal (2+2) Cycloaddition of \(\alpha\), \(\beta\)-Unsaturated Ethers

### Table 5 The kinetic parameters for the cycloaddition reactions in CHCl₃

<table>
<thead>
<tr>
<th>Donor</th>
<th>10°C</th>
<th>20°C</th>
<th>30°C</th>
<th>(E_a)</th>
<th>(\Delta S^{\pm})</th>
</tr>
</thead>
<tbody>
<tr>
<td>cis-PEE</td>
<td>(k_r)</td>
<td>(2.5 \times 10^{-2})</td>
<td>(3.1 \times 10^{-2})</td>
<td>(4.1 \times 10^{-2})</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>(k_r')</td>
<td>(2.8 \times 10^{-2})</td>
<td>(3.1 \times 10^{-2})</td>
<td>(3.7 \times 10^{-2})</td>
<td>5.2</td>
</tr>
<tr>
<td>IBEE</td>
<td>(k_r)</td>
<td>(4.4 \times 10^{-2})</td>
<td>(6.8 \times 10^{-2})</td>
<td>(1.0 \times 10^{-1})</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>(k_r')</td>
<td>(4.4 \times 10^{-3})</td>
<td>(6.4 \times 10^{-3})</td>
<td>(9.1 \times 10^{-3})</td>
<td>6.8</td>
</tr>
<tr>
<td>VEE</td>
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<td>(1.5 \times 10^{-1})</td>
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<td>(1.0 \times 10^{-1})</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>(k_r')</td>
<td>(1.1 \times 10^{-2})</td>
<td>(1.0 \times 10^{-2})</td>
<td>(1.0 \times 10^{-2})</td>
<td>7.3</td>
</tr>
<tr>
<td>VI-BE</td>
<td>(k_r)</td>
<td>(2.0 \times 10^{-2})</td>
<td>(2.0 \times 10^{-2})</td>
<td>(2.0 \times 10^{-2})</td>
<td>7.3</td>
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<tr>
<td></td>
<td>(k_r')</td>
<td>(1.0 \times 10^{-4})</td>
<td>(1.0 \times 10^{-4})</td>
<td>(1.0 \times 10^{-4})</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Note: a) sec⁻¹  b) M⁻¹ sec⁻¹  c) kcal mol⁻¹  d) e. u.

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formation seems not to be explained concurrently merely in terms of the electronic structure of the ground state of the reactant ethers; likely the chemical non-crossing rule cannot be assumed in this type of cycloadditions. In order to explain the implication of the negative slope of the plots for cis-PEE and IBEE in Fig. 10, some steric effect is to be taken account of in addition to the electronic effect as in the case of Ag⁺-unsaturated ether complexes described before. The activation entropy of the cycloaddition is very large negative; ca. -40 e. u. in Scheme (1) and ca. -50 e. u. in Scheme (2), while the entropy of the complex formation is ca. -10 e. u. Then, it seems that the configuration between the donor and acceptor in the transition state is so rigid that the steric effect overshadows the electronic effect of \(\pi\)-methyl groups, while in the complex state the configuration is so labile that the electronic effect is more significant than the steric effect.

Next we studied the stereochemistry of the cycloaddition of TCNE with PEE in the isomer range 96–30% of cis-PEE in CH₂Cl₂. The reactant isomer composition was determined by vapor phase chromatography and NMR. The product isomer composition was determined by NMR characteristic absorption intensities: cis-adduct: \(\tau=6.3\) (Hₘ) and \(\tau=5.0\) (Hₖ); trans-adduct: \(\tau=6.6\) (Hₘ) and \(\tau=

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27) R. D. Brown, *Quart. Rev.*, 6, 63 (1952)
The reactant isomer composition is always equal to the product isomer composition in each run. This result suggests that the cycloaddition is stereoselectively cis, in other words, it will follow $2\pi_s + 2\pi_s$ approach.

Why is the unsaturated ether "REACTIVE" and is the olefin "NONREACTIVE" as shown in Table 1, though two kinds of the donors have similar CT bands and NMR spectra? This reactivity difference should mainly be attributed to considerable transition state stabilization of the TCNE-ether system. The transition state of the TCNE-olefin system is isoconjugate to antiaromatic cyclobutadiene when $2\pi_s + 2\pi_s$ approach is followed. Similarly, the transition state of the TCNE-ether system is isoconjugate to cyclobutadiene in the same approach. In the former case resonance does not reduce the antiaromaticity of cyclobutadiene, while in the latter case resonance can effectively destroy the antiaromaticity as seen in Fig. 12. This presumption is supported by the fact that "Push-Pull" cyclobutadiene is isolated stably.

Correlation diagram

$2\pi_s + 2\pi_s$ thermal cycloaddition is symmetrically forbidden from the Woodward-Hoffmann rule\(^{29}\). Why does our cycloaddition proceed under very mild conditions in this pathway? In order to consider this question we prepared the molecular orbital correlation diagrams for two cases. Fig. 13 shows the correlation diagram for a typical $2\pi_s + 2\pi_s$ non-polar cycloaddition i.e. ethylene-butene-2 system. The energy levels of the MO's of the cycloaddends and the transition state (TS) complex have been determined by reference to ionization potential and ultraviolet spectroscopy and also by the EHMO calculation. Moreover, Fig. 14 shows the correlation diagram for a typical $2\pi_s + 2\pi_s$ polar cycloaddition.

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Charge-Transfer Interaction and Successive Thermal (2+2) Cycloaddition of $\alpha$, $\beta$-Unsaturated Ethers 37

*i.e. IBEE-TCNE system. We will compare these two diagrams. First, the diagram in Fig. 13 shows that the lowest state of the TS complex correlates with a diexcited cyclobutane product and accordingly the reaction is thermally forbidden. In order to render the reaction allowed in $2\pi$+$2\pi$ approach two electrons must be promoted from $\phi_2$ to $\phi_3$. This would need the expenditure of considerable energy since the energy gap between $\phi_2$ and $\phi_3$ can be estimated to be 4.5 eV. Such a considerably much energy is not supplied by means of thermal agitation, and then a non-polar $2\pi$+$2\pi$ thermal cycloaddition cannot proceed. Secondly, the diagram in Fig. 14 shows the same shape as before and the reaction is formally not allowed. Unlike the previous case, however, the promotion of two electrons from $\phi_2$ to $\phi_3$ would require only small energy expenditure since its energy gap is very small: ca. 1 eV. Hence a polar $2\pi$+$2\pi$ thermal cycloaddition may well occur under mild conditions.

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