Intrinsic and Thermodynamic Effects on the Structure and Energy of the S_N2 Transition State*

Ikchoon Lee and Heon Su Seo

Department of Chemistry, Inha University, Inchon 160. *Received August 19, 1986*

Two contributions to the activation barrier of the S_N2 reaction, intrinsic and thermodynamic, are discussed in connection with the predictive power of various rate–equilibrium relationships. It has been shown that the PES models can only give correct predictions of changes in structure and energy of the transition state if the activation barrier is dictated by the thermodynamic factor. We concluded that the identity and dissociative S_N2 reactions are dominated by the intrinsic component while associative S_N2 reactions are predominantly of thermodynamic controlled. Thus in the former cases, the PES models fail, whereas in the latter cases predictions based on the intrinsic factor, the quantum mechanical models, fail. Finally in a general case of equal contributions by thermodynamic and intrinsic factors, the S_N2 reaction proceeds by a synchronous process with zero net charge on the reaction center, for which predictions of substituent effects will be the same as for the intrinsic control case.

1. Introduction

It is important to recognize and understand the factors responsible for governing chemical reactivity in developing experimental criteria for measuring, and theoretical models for predicting, substituent effects on the structure of the transition state (TS). Experimentally, selectivity parameters such as ρ, m, α and β have all been used for assessing changes in the TS structure.[1] The theoretical basis for predicting changes in the TS structure has originally been provided by the Bell–Evans–Polanyi (BEP) principle[2] and the closely related Hammond postulate.[3] From these basic ideas various potential energy surface (PES) models have recently been developed. The most prominent of these are those of Thornton,[4] More O'Ferral,[5] Harris and Kurz,[6] and Jencks.[7] All these models have one important feature in common: they provide with a qualitative means of estimating the effect of substitutents on the structure and energy of the TS based on thermodynamic properties of the reaction system. Thus these models correlate changes in the structure and energy of the TS with relative stabilities of reactants, products and intermediates. Depite the many successes of the PES models, a number of cases have emerged where they fail to apply.

Recently progress in the gas–phase studies of ion–molecule reactions,[8] in conjunction with Marcus theory,[9] has provided valuable insights into a conceptual appreciation of "intrinsic" reactivity involved in one of the most extensively studied reactions in organic chemistry, the S_N2 reaction.

The quantitative rate–equilibrium relationship was first formulated by a theory developed by Marcus.[9a] His equation, (1), correlates the activation barrier, ΔE,* with the overall energy of reaction, ΔE°, and the "intrinsic" barrier, ΔE_0^{*}, that would

$$\Delta E^{*}=\frac{(\Delta E^{\circ})^2}{16\Delta E_0^{*}}+\Delta E_0^{*}+1/2\,\Delta E^{\circ} \tag{1}$$

exist in the absence of any thermodynamic driving force, *i.e.*, when $\Delta E^{\circ}=0$. The intrinsic barrier may be thought of as the purely kinetic contribution to the reaction barrier. The generality of eq.(1) to chemical reactions has only become apparent more recently with the advent of experimental as well as theoretical means of determining intrinsic barrier, ΔE_0^{*}.

In this work, we will show that the Marcus equation is of the fundamental and general nature and the predictions of changes in the TS structure of the S_N2 reactions are only possible, in general, by considering both contributions, ΔE° and ΔE_0^{*}, to the activation barrier ΔE_0^{*}.

Three distinctive cases will be discussed: (I) The ΔE^{*} is dependent only on ΔE°, when the variation of ΔE_0^{*} is relatively small or negligible, *i.e.*, $\delta\Delta E_0^{*}\cong 0$. In this case, the reaction will be a "thermodynamic control" process. (II) The ΔE^{*} is dependent only on ΔE_0^{*}, when the variation of ΔE° is small or negligible, *i.e.*, $\delta\Delta E^{\circ}\cong 0$. This will be a "intrinsic control" process. (III) The ΔE^{*} is dependent on both ΔE° and ΔE_0^{*}, when the variation of either of them cannot be disregarded, *i.e.*, $\delta\,\Delta E^{\circ}\cong\delta\Delta E_0^{*}$. This will be the more general case, but in reality cases where approximations (I) and (II) apply are more common.

2. Thermodynamic Control

In any approach to chemical reactivity using rate–equilibrium relationships,[1] the effect of substituents on the structure and energy of the TS is interpreted in terms of partinent equilibrium constant, K, or the overall energy of reaction ΔE°. For example, the Bronsted relation,[10] (2), can be

$$\mathrm{d}\ln \mathrm{k} = \mathrm{B}\,\mathrm{d}\ln \mathrm{K} \tag{2}$$

$$\mathrm{d}\Delta E^{*} = \mathrm{B}\,\mathrm{d}\,\Delta E^{\circ} \tag{3}$$

transformed into eq.(3), which is none other but the BEP principle.[2] The slope, B, of the empirical relationship between rate constants, k, and acidity or basicity constants, K, in eq.(2) is a proportionality constant between activation barrier, ΔE^{*}, and energy of reaction, ΔE°, in eq.(3). Equation (3) implies that a small variation in ΔE°, a thermodynamic quantity, is reflected in a corresponding variation in ΔE^{*}; barrier height changes are solely dictated by the changes in reaction exothermicity ($\Delta E^{\circ}<0$) or endothermicity ($\Delta E^{\circ}>0$). Moreover, in a very exothermic (endothermic) reaction, the Hammond postulate suggests that the TS should resemble the reactants (products) structurally, and that it should be of similar energy so that $\Delta E^{*}\cong 0$ ($\Delta E^{*}\cong\Delta E^{\circ}$) and B≅0 (B≅1).

Various PES models[3-7] also correlate the structure of the

---

*Determination of Reactivity by MO Theory (Part 48)

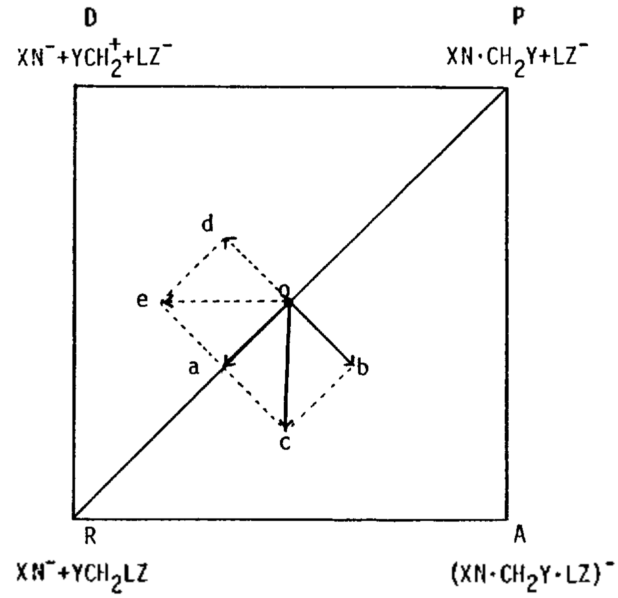


Figure 1. PES diagram for the S_N2 reaction of $XN^- + YCH_2LZ \rightarrow XNCH_2Y + LZ^-$.

TS with thermodynamic stabilities of the species involved in the reaction system. Let us consider the PES diagram approach of More O'Ferrall[5] in detail.

For a typical S_N2 reaction (4),[11] the PES diagram (Figure 1)

$$XN^- + YCH_2LZ \rightarrow XNCH_2Y + LZ^- \tag{4}$$

consists of four corners, R(reactants), P(products), A(associated) and D(dissociated), with a TS on the diagonal line connecting R and P. Suppose the nucleophile was changed to a stronger one e.g. by introducing X = electron donating group (EDG), then the corners P and A are stabilized. According to the Hammord[3] (shift to a) and anti-Hammond[4] (shift to b) rules, the TS will now shift to point c, which is obtained as a vactor sum of $\vec{oa}$ and $\vec{ob}$.[5] Thus the PES diagram approach predicts that an increase in the nucleophile strength will decrease the degree of carbon-leaving group (C-L) bond cleavage (BB↓) and has little effect on the degree of nucleophile-carbon (N-C) bond formation (BF↔). On the other hand, change to a better leaving group, *e.g.* by introducing Z = electron withdrawing group (EWG), will stabilize corners D and P, and the TS will shift to e so that a TS with less N-C bond formation (BF↓) and little change in C-L bond breaking (BB↔) is predicted. Finally if we have an EWG in the substrate *e.g.* Y = EWG, then the corner A will be stabilized and the TS will shift to b; a tighter TS with greater degree of N-C bond formation (BF↑) and less C-L bond breaking (BB↓) will be obtained. Predictions of substituent effects on the changes in the TS structure based on the PES diagram model are summarized in Table 1 under the columns of "thermodynamic control".

Reactions of benzenesulfonyl chlorides with anilines in MeOH-MeCN solvents, (5), have been shown to proceed by an associative S_N2 mechanism.[12] The experimental result of

$$XC_6H_4NH_2 + YC_6H_4SO_2Cl \rightarrow YC_6H_4SO_2NHC_6H_4X + HCl \tag{5}$$

positive ρ_Y (reaction constant with respect to substituent Y) indicated that negative charge develops at the reaction center (*S* atom) in the TS as a result of greater degree of N–S bond formation than the S–Cl bond cleavage. A greater positive ρ_Y for a stronger nucleophile ($\rho_Y = 1.07$ for X = p-CH_3) compared to a weaker one ($\rho_Y = 0.57$ for X = m-NO_2) is therefore an indication of a tighter TS for the former, since a decrease in the S–Cl bond cleavage (BB↓) with a possible increase in N-S bond formation (BF↑) will lead to an increase in the ρ_Y value. Moreover a greater ρ_N value obtained for the substrate with an EWG (Y = p-NO_2) indicates an increase in N-S bond formation (BF↑). These results are in accord with the predictions of the PES model in Table 1.

Table 1. Prediction of Changes in the S_N2 TS Structure with Substituents on the Nucleophile(X), Substrate(Y), and Leaving Group(Z)[a]

	I Thermodynamic Control		II Intrinsic Control	
S_N2 Type	Associative		Identity, Dissociative Synchronous	
TS Structure	B F	B B	B F	B B
X = EDG	↔	↓	↑	↑
Y = EWG	↑	↓	↑	[b]↑(↓)
Z = EWG	↓	↔	↑	↑

[a] Arrows ↑,↓ and ↔ denote increase, decreace, and no or little change, respectively. [b] Depending on the polarization (↓) or the charge transfer control (↑), we have two different effects[15].

Another example in this category is the reaction of phenacyl benzenesulfonates with anilines,[13] (6). This reaction is also known to proceed by an associative S_N2 mechanism.[13] Our

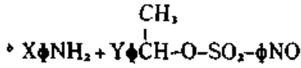
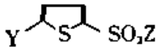
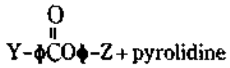
$$\begin{aligned}&XC_6H_4NH_2 + YC_6H_4COCH_2OSO_2C_6H_4Z \rightarrow \\ &XC_6H_4NHYC_6H_4COCH_2 + H^+ + SO_3C_6H_4Z^-\end{aligned} \tag{6}$$

results have shown that a stronger nucleophile (X = p-CH_3O) has a smaller ρ_Z (reaction constant with respect to substituent Z) value (of 1.07) compared to that of the unsubstituted nucleophile ($\rho_Z = 1.34$ for X = H) indicating a decrease in the C-O bond breaking (BB↓), whereas a better leaving group (Z = p-Cl) gave a smaller magnitude of ρ_X (= −1.99) than that for a poor leaving group ($\rho_X = -2.40$ for Z = p-CH_3) showing a decrease in the N-C bond formation (BF↓). All these trends of associative S_N2 reactions are in good accord with the predictions of the PES model,[3-7] (see also Table 2).

In this connection we should note that in the associative S_N2 reactions bond breaking, and hence the deformation of the substrate at the TS, is still small. This means that no significant charge transfer from the nucleophile to the antibonding orbital (σ^*) of the cleaving bond (C-L) takes place at the TS.[14] As a result, charge localization on the reaction center and leaving group, C^+C^-, will be negligible. Such charge separation is known to occur by two types of electron reorganization interactions:[15] polarization, E_{pl}, and charge transfer, E_{ct}, interactions. Since the polarization is a long range effect of electron transfer within the substrate due to electrostatic field of approaching nucleophile, the charge localization to the C^+L^- structure will be inefficient with little bond breaking. Thus the electron reorganization in the associative S_N2 process will take place mainly by polarization interaction.

A relatively tight TS in the associative S_N2 mechanism will also be evidence by a relatively large cross interaction cons-

Table 2. Examples of Predictions of Substituent Effects on TS Structure

Reaction		[a] Effect of Substituent	Type of Reaction	[c]Type of Control
[b]  $X\phi NH_2 + Y\phi\overset{CH_3}{\overset{\vert}{C}}H\text{-}O\text{-}SO_2\text{-}\phi NO_2$	$\xrightarrow{MeOH}$	X = EDG BF↑ Y = EWG BF↑	Dis.S_N2	MeOH
[d] $X\text{-}\phi\text{-}S^- + Y\text{-}\phi CH_2\text{-}N(CH_3)_2\text{-}\phi\text{-}Z$	→	Z = EWG BF↑, BB↑	Dis. S_N2	II
[e] $X\text{-}\phi NH_2 + \phi CH_2Z$	→	Z = Better L.G. BF↑	Dis.S_N2	II
[f]  + Nu^-	→	Y = EWG BF↑, BB↓	Ass.S_N2	I
[g]  $Y\text{-}\phi\overset{O}{\overset{\Vert}{C}}O\phi\text{-}Z$ + pyrolidine	→	Y = EWG BB↓	Ass.S_N2	I

[a] All symbols and abbreviations are as defined in the text; [b] I. Lee, H.K. kang and H.Y. Kim, Unpublished results; [c] I and II are "thermodynamic" and "intrinsic" control, respectively; [d] K.C. Westaway and S.F. Ali; *Can. J. Chem.*, **57**, 1354 (1979); [e] F.P. Ballistreri, E. Maccarone and A. Mamo, *J. Org. Chem.*, **41**, 3364 (1976); [f] A. Acoria *et al.*, JCS. Perkin II, 226 (1981); [g] Ref. le

Table 3. Experimental and Theoretical Values of $\Delta E_0^\ddagger$ (kcal/mol) for ($N^- + CH_3N$)

N	$\Delta E_0^\ddagger$	
	Experimental[8c]	Theoretical[17]
HCC	41.3	50.4
CN	35.0	43.8
CH_3O	26.6	23.5
CH_3S	24.2	15.6
F	26.2	11.7
Cl	10.2	5.5

tant ρ_{ij}, since the magnitude of the cross interaction constants has been shown to be inversely proportional to the distance between the two substituents *i* and *j*.[16]

We conclude that the "thermodynamic control" reaction such as the associative S_N2 reaction has the following features: (i) Negative charge develops at the reaction center of the substrate. (ii) Polarization interaction is the predominant contribution to the electron reorganization within the substrate. (iii) The structure and energy variation can be predicted by the PES models. (iv) The cross interaction constants are relatively large. Some more examples are listed in Table 2.

3. Intrinsic Control

The quantitative understanding of rate-equilibrium relationships has been greatly catalyzed by the introduction of Marcus equation (1). According to (1), the activation barrier, ΔE^*, is not a function of thermodynamic quantity, ΔE°, alone, but it has another non-thermodynamic, a purely kinetic component, $\Delta E_0^\ddagger$. The experimental[8] as well as theoretical[17] studies on the gas-phase S_N2 identity reactions have provided a direct means of determining the "intrinsic barrier" $\Delta E_0^\ddagger$, and enabled to demonstrate the generality of the Marcus equation. Important findings from these studies are: (i) The concepts of nucleophilicity and leaving group ability becomes equivalent. (ii) The TS structure parameters, such as bond lengths and angles, can be correlated with the exothermicity, ΔE°, but the deformation energies are found to be linear with $\Delta E_0^\ddagger$. (iii) $\Delta E_0^\ddagger$ can be correlated with the methyl cation affinity (MCA) of L^- (eq.7). where D°, EA and IP are bond

$$MCA(L^-) = \Delta H^\circ = D^\circ(CH_3\text{-}L) - EA(L) + IP(CH_3) \quad (7)$$

$$\text{for } CH_3L \rightarrow CH_3^+ + L^- \quad (8)$$

dissociation energy, electron affinity and ionization potential, respectively. (iv) The additivity rule holds so that $\Delta E_0^\ddagger(AB) = (\Delta E_0^\ddagger(AA) + \Delta E_0^\ddagger(BB))/2$.

It is of utmost importance to recognize the close interrelationship between the intrinsic barrier and the bond breaking process in the S_N2 reaction. Wolfe *et al.*[18] have shown that $\Delta E_0^\ddagger$ has good linear correlation with the energy of stretching deformation, the energy needed to stretch the cleaving bond to the length in the TS structure. It is therefore apparent that the instrinsic barrier parallels the leaving ability, *i.e.*, the easiness of bond breaking, while the energy of reaction, ΔE°, is mainly dominated by the nucleophilicity *i.e.*, the facility of bond formation. This is why the PES, a thermodynamic control, model applies to the associative S_N2 processes, for which bond formation is more important than bond breaking. The overall S_N2 process will involve the bond-breaking and -formation, and hence the activation barrier ΔE^* will be a function of $\Delta E_0^\ddagger$ and ΔE°. In this connection it is interesting to find

$$S_N2\ TS = \text{bond breaking} + \text{bond formation}$$

$$\Delta E^* = f(\Delta E_0^\ddagger, \Delta E^\circ) \rightarrow \text{eq. (1)} \quad (9)$$

a derivation of an expression for a general inter-relationship between TS bond extensions, $d = R_{NC} + R_{CL}$ where R's denote distances between reaction center and nucleophile and leaving group at the TS, and the energy barrier to reaction ΔE^*.[19] Varandas *et al.*,[19] have shown that the intrinsic barrier is associated with an entropy parameter in this expression. This is reasonable since a greater degree of bond breaking should result in a greater entropy of the TS.

It is well established that reactivity, the reverse order of the intrinsic barrier, in the identity exchange series (see Table 3), in the gas phase as well as in solution, follows the leaving group ability, despite the fact that at the same time nucleophilicity itself was changing drastically.[3d] Thus increase in the resonance contribution of $N^-CH_3^+L^-$ structure to the TS will lead to a lower intrinsic barrier.

On the other hand the intrinsic nucleophilicity should be in the same order as the intrinsic leaving group ability. The

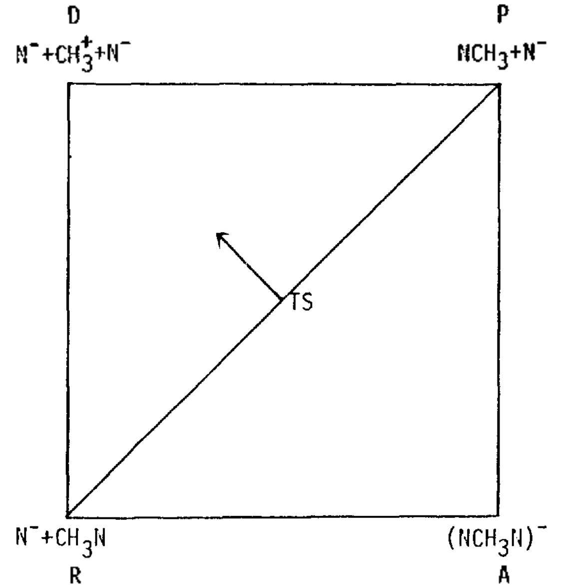


Figure 2. PES diagram for the identity S_N2 reaction, (R = P). A and D represent associated and dissociated species, respectively.

intrinsic barrier actually increases with the basicity of the nucleophile, so that the "intrinsic nucleophilicity" decreases with increasing basicity. Since basicity is reflected in thermodynamic instability, the more basic a nucleophile, the more exothermic is its substitution reaction, and the lower the barrier ΔE^*. Consequently, the observed empirical order of nucleophilicity is mostly due to the increased thermodynamic driving force associated with a strong base in bond formation. In the identity S_N2 reaction, this thermodynamic (exothermic) driving force in bond formation is exactly counter balanced by the endothermic bond breaking of the same bond at the TS so that $\Delta E^\circ = 0$.

The fact that ΔE_0^* can be correlated with the MCA[8c] may be taken as evidence in support of the close dependence of ΔE_0^* on bond stretching at the TS, since the bond stretching will certainly enhance a charge localized structure, CH_3^+ L^-, used in the definition of the MCA. Another compelling evidence in support of this contention comes from results of the experimental studies on methyl transfer between arensulfonates,(10).[20] Lewis *et al.*[20] have shown that the experimental Hammett reaction constant, ρ_{XX}, for the identity reaction had a positive value of 0.6. They concluded that the most probable source of this substantial positive ρ is the contribution of the charge localized structure, CH_3^+ OS_3ArX^- to the TS.

$$XArSO_3^- + MeO_3SArX \rightarrow XArSO_3Me + O_3SArX^- \qquad (10)$$

This is reasonable because for the identity S_N2 reaction (10) the experimental ρ value (ρ_{XX}) can be decomposed as (11).

$$\rho_{XX} = \rho_{X(N)} + \rho_{X(L)} \qquad (11)$$

where $\rho_{X(N)}$ and $\rho_{X(L)}$ are two components due to effects of the nucleophile and leaving goup, respectively. The $\rho_{X(N)}$ is expected to be negative since charge is transferred from the nucleophile and the negative charge of the nucleophile will decrease, $\rho_{X(N)}<0$; similarly the $\rho_{X(L)}$ will be positive, $\rho_{X(N)}>0$. Thus the experimentally obtained positive ρ_{XX} clearly shows that in the identity reaction the leaving group effect predominates the ΔE_0^*, with little effect of nucleophilicity. This is however natural if we think of the bond distances involved in the TS, R_{CN} and R_{CL} (for a general case of eq.4). In the identity S_N2 TS structure (I), $R_{CN} = R_{CL}$; however in terms

$$\underset{R_{CN}}{N^+ \text{-------}} C^+ \underset{R_{CL}}{\text{-------} L^-} \qquad (I)$$

of bond lengths in molecules $XNCH_2Y$ and YCH_2LZ, $R_{x,CN}$ and $R_{y,CL}$, the differences are normally considerable, *i.e.*, $\Delta R = R_{CL} - R_{x,CL} \neq R_{CN} - R_{x,CN}$ = large, so that bond breaking is considerable, $\Delta R(CL)$ = large, while bond formation is relatively small since the distance between N and C is still large and no significant bond formation is achieved yet, $\Delta R(CN)$ = large = little bond formation. Thus the TS structure for an identity S_N2 reaction represents actually a greater degree of bond breaking with little bond formation. Therefore as a whole, ΔE^* will be governed by a bond breaking process, contribution of bond formation being relatively small. This is why we have reactivity trends in parallel with that of the leaving group ability in the identity exchange reactions.[8d]

We conclude that the intrinsic energy factor becomes dominant in the Marcus equation when bond stretching is relatively large at the TS, and in the S_N2 reaction, this situation will be realized if bond breaking proceeds ahead of bond formation as in the identity and dissociative S_N2 reactions. In this type of S_N2 processes, the reaction center will be positively charged, in contrast to the negative charge development in the associative S_N2 reactions. When however the activation barrier is dominated by the intrinsic barrier, no correlation is normally expected between ΔE^* and ΔE_0 and hence the PES models fail. In fact Mitchell *et al.*,[18] have clearly shown this failure of the PES models in predicting the changes in structure and energy of the identity S_N2 reactions, for which ΔE^* is only dependent upon ΔE_0^*. They have demonstrated using the PES diagram in Fig. 2 that in the identity reaction, $N^- + CH_3N = NCH_3 + N^-$, a loser TS is predicted when N = H is replaced by N = Cl, since $(Cl^- + CH_3^+ + Cl^-)$ is at least 40 kcal/mol more stable than $(H^- + CH_3^+ + H^-)$ and hence the TS will shift towards the corner D. However deformation indices found were 21.1 and 58.0 for N = Cl and H respectively, indicating far more distortion from the original molecule and hence looser TS for X = H. Thus the PES, a thermodynamic, model fails to account for the identity S_N2, an intrinsic control, reactivity.

Results of the dissociative S_N2 reactions of benzylbenzene sulfonates with anilines, (12), revealed that a better nucleophile ($X = p\text{-}CH_3O$) as well as a better leaving group ($Z = p\text{-}NO_2$)

$$XC_6H_4NH_2 + YC_6H_4CH_2OSO_2C_6H_4Z \rightarrow$$
$$XC_6H_4NHYC_6H_4CH_2 + SO_3C_6H_4Z^- + H^+$$

have a more product-like TS,[21] in direct contradiction to the predictions based on the PES models. The negative ρ_Y values obtained indicated positive charge development at the reaction center at the TS, so that an intrinsic control process.

Other examples belonging to this category have been reviewed by Pross and Shaik.[22a] Additional examples are summarized in Table 2 together with relevant experimental results. These failures of the PES models emphasize again that the predictions of the TS structure by the PES models are not feasible in the cases where the barriers ΔE^* are not dominated by ΔE° but dictated by ΔE_0^*. Predictions of the changes in structure of the TS for these ractions are, however, possible using VB[22] and energy decomposition MO models[15] developed for intrinsic control processes. These are summarized in Table 1.

For the intrinsic controlled processes, the TS will have highly charge transferred localized structure (CH; L^-) due to substantial charge transfer from the nucleophile to the sigma *anti*-bonding orbital of the cleaving bond (C-L) and hence electron reorganization is dominated by the charge transfer interaction, E_{ct}.

Recently Process and Shaik have shown that the surface crossing diagram model using valence bond configuration mixing (VBCM) method can accommodate all experimental results of substituent effects on the S_N2 TS structure.[22a] Their qualitative VB method can be regarded as a thermochemical quantum method, since this approximation combines thermochemical quantities such as bond energies, IPs and EAs, with the quantum mechanical quantities such as delocalization energies; the two energies, ΔE° and ΔE_0^*, are naturally incorporated into the activation barrier, ΔE^*, as Marcus theory postulates. Hence the VBCM approach[22] should provide a general model for prediction of substituent effects on the S_N2 TS structure accommodating the two extreme cases of thermodynamic and intrinsic controlled activation processes. However the predictions are found to be correct only for those experimental results of the intrinsic controlled reactions, and the model fails to account for the cases of the thermodynamic controlled processes. This is also true with the decomposition of interaction energy (MO) model.[15] For example a stronger nucleophile and a better leaving group in the associated S_N2 reactions, (5) and (6), gave decreases in bond breaking and bond formation; the quantum mechanical (QM) models however predict increases in bond breaking and bond formation in contrast to the experimental results. Thus we should be aware that the QM models over-stress intrinsic nature of chemical reaction by focussing on the deformation energy of the substrate in the TS.

We conclude that the intrinsic controlled processes such as the identity and the dissociative S_N2 reactions have the following features in common: (i) Positive charge develops at the reaction center. (ii) The structural changes of the TS are dictated by the intrinsic factor, which is turn is dominated by bond stretching deformation giving charge localized carbocationic TS structure. (iii) Charge transfer interaction is the dominant electron reorganization. (iv) The PES models fail to predict the changes in the structure and energy of the TS. (v) The cross interaction constants, ρ_{ij}, will be relatively small, especially those involving with leaving group, *i.e.*, ρ_{XZ} and ρ_{YZ}[16].

III. Thermodynamic + Intrinsic Control

Finally we can think of a more general case where both ΔE° and ΔE_0^* contribute equally to the activation barrier ΔE^* in eq. (1). In this case both bond breaking and bond formation proceed to nearly the same extent and constitutes a synchronous S_N2 type reaction.

$$N^{+}--- C^{\circ} ------L^{-} \tag{II}$$

In the synchronous S_N2 TS, (II), bond formation is also considerable so that ΔE° contributes substantially to ΔE^* in contrast to the identity S_N2 reactions, where the degree of bond formation is meager and the contribution of ΔE° was found to be small or negligible. Since bond breaking takes place to the same degree as bond formation, the net charge at the reaction center will be zero. Naturally this sort of situation arises only when the TS is past beyond the structure of the identity exchange case along the reaction coordinate. Zero charge on the reaction center is also in contrast to the identity reaction where the reaction center has a net positive charge. In this case, $|\rho_X| \cong |\rho_Z|$ and $\rho_Y \cong 0$.

The substituent effects on the TS structure will be similar to the intrinsic control case, since the synchronous nature of bond breaking and bond formation would require the effects in the same direction, as for the intrinsic control case in Table 1. In this case the cross interaction constant ρ_{XY} will be relatively large, but ρ_{YZ} and ρ_{XZ} will be small.[16]

A corollary of the Mercus equation is that a condition for obtaining a linear free energy relation (LFER) is the constant ΔE_0^* for the series of reaction under study. Reactions with the same ΔE_0^* will lie on the sameΔE^* vs ΔE° curve and if in addition to this, the rections span a relatively small range of ΔE°, a LFER is obtained.

Acknowledgement. We wish to thank the Ministry of Education and the Korea Science and Engineering Foundation for support of this work.

References

1. (a) W.J. Albery and M.M. Kreevoy, *Adv. Phys. Org. Chem.*, **16**, 87(1978); (b) A.J. Kresge, Acc. Chem. Res., **8**, 354 (1975); (c) A. Pross, *Adv. Phys. Org. Chem.*, **14**, 69 (1977); (d) D.J. McLennan, *Tetrahedron*, **31**, 2999 *J. Chem.*, **63**, 1642 (1985).
   W.P. Jencks, *Chem. Rev.*, **85**, 511 (1985).
2. M.J.S. Dewar, "The MO Theory of Organic Chemistry", McGraw-Hill, New York, 1969, p284.
3. G.S. Hammond, *J. Am. Chem. Soc.*, **77**, 334 (1955).
4. E.R. Thornton, *ibid.*, **89**, 2915 (1967).
5. R.A. More O'Ferrall, *J. Chem. Soc.* B, 274 (1970).
6. J.C. Harris and J.L. Kurz, *J. Am. Chem. Soc.*, **92**, 349 (1970).
7. D.A. Jencks and W.P. Jencks, *ibid.*, **99**, 7948 (1977).
8. (a) M.J. Pellerite and J.I. Brauman, *ibid.*, **102**, 5993 (1980); (b) W.N. Olmstead and J.I. Brauman, *ibid.*, **99**, 4219 (1977); (c) M.J. Pellerite and J.I. Brauman, *ibid.*, **105**, 2672 (1983); (d) C-C. Han, J.A. Dodd, and J.I. Brauman, *J. Phys. Chem.*, **90**, 471 (1986).
9. (a) R.A. Marcus, *Ann. Rev. Phys. Chem.*, **15**, 155 (1965); (b) J.R. Murdoch, *J. Am. Chem. Soc.*, **94**, 4410 (1972); (c) D.J. McLennan, *J. Chem. Ed.*, **53**, 348 (1976); (d) E. G. runwald, *J. Am. Chem. Soc.*, **107**, 125 (1985).
10. J.N. Bronsted and K. Pedersen, *Z. Phys. Chem.*, **108**, 185 (1924).
11. Throughout this paper, X, Y, and Z will be used to denote

substituent in the nucleophile, substrate and leaving group respectively, and N and L, the nucleophile and leaving group respectively.

12. I. Lee and I.S. Koo, *Tetrahedron*, **39**, 1803 (1983).
13. I. Lee, C.S. Shim, and S.Y. Chung, Unpublished results.
14. K. Fukui and H. Fujimoto, *Bull. Chem. Soc. Japan*, **42**, 3393 (1969).
15. I. Lee and S.C. Sohn, *Bull Korean Chem. Soc.*, **7**, 186 (1986).
16. I. Lee and S.C. Sohn, *J. Chem. Soc. Chem. Commun.*, 1055 (1986).
17. S. Wolfe, D.J. Mitchell, and H.B. Schlegel, *J. Am. Chem. Soc.*, **103**, 7692, 7694 (1981).
18. D.J. Mitchell, H.B. Schlegel, S.S. Shaik, S. Wolfe, *Can. J. Chem.*, **63**, 1642 (1985).
19. A.J.C. Varandas and S. J. Formosinho, *J. Chem. Soc. Faraday 2*, **82**, 953 (1985).
20. E.S. Lewis and D.D. Hu, *J. Am. Chem. Soc.*, **106**, 3292 (1984).
21. (a) I. Lee, W.H. Lee, S.C. Shon, and C.S. Kim, *Tetrahedron*, **41**, 2635 (1985); (b) I. Lee, S.C. Sohn, C.H. Gang, and Y.J. Oh, *J. Chem. Soc. Perkin* 2, 1631 (1986). I. Lee, S.C. Shon, Y.j. Oh, and B.C. Lee, *Tetrahedron*, **42**, 4713 **(1986).**
22. **(a)** A. Pross and S.S. Shaik, *J. Am. Chem. Soc.*, **103**, 3702 (1981); (b) S.S. Shaik and A. Pross, *ibid.*, **104**, 2708 (1982); (c) A. Pross and S.S. Shaik, *ibid.*, **104**, 187 (1982); (d) S.S. Shaik, *ibid.*, **105**, 4359 (1983).

Synthesis of (Z)-, and (E)-8-Dodecen-1-yl Acetate, The Sex Pheromone of the Oriental Fruit Moth, Grapholitha Molesta by Stereochemical Control in Wittig Olefination

Suk-Ku Kang*, **Jung-Hawn Kim, and Yaung-Chul Shin**

Department of Chemistry, Sung Kyun Kwan University Natural Science Campus, Suwon 170

Received August 25, 1986

Stereochemical control of the Wittig reaction of the primary aldehyde, 8-acetoxyoctan-1-al **(7)** with the nonstabilized alkylide, triphenylphosphonium n-butylide **(6)**, was achieved by controlling the reaction conditions including solvent, temperature and inorganic salts. These conditions can be applied to the direct synthesis of the mixture of (Z)-, and (E)-8-dodecen-1-yl acetate, the sex pheromone of the oriental fruit moth, *Grapholitha molesta*. The primary aldehyde, 8-acetoxyoctan-1-al **(7)** was synthesized from 1,8-octanediol which is cheap and readily available.

Introduction

The sex pheromone of the oriental fruit moth, a major economic pest of apple, peach, and other fruits in Korea[1] was identified as (Z)-8-dodecen-1-yl acetate **(1)** by Roelofs *et al.*[2] in 1969. Later, the requirement for attractancy of an isomeric mixture containing a samll amount of (E)-8-dodecen-1-yl acetate **(2)** was demonstrated.[3] In 1979, Carde *et al.*[4] isolated three volatile components from gland of Grapholitha molesta Busk virgin females and identified as (Z)-, and (E)-8-dodecen-1-yl acetate and (Z)-8-dodecen-1-ol **(3)**. It was reported[5] that dodecanol **(4)** act as a synergist and dodecenyl acetate **(5)** act as an inhibitor (Figure 1).

Catches of the oriental fruit moth males at traps baited with (Z)-8-dodecen-1-yl acetate were much influenced by small amounts of the (E)-isomer. Even if the biological activity depends on place and climate, the ratio of (Z)-to (E) at 6∼15% gave the best capture. 93% (Z)-and 7% (E)-8-dodecen-1-yl acetate, the synthetic pheromone was known as Orfralure.[6]

The oriental fruit moth, *Grapholitha molesta*, is not attracted at all by light traps, therefore, survey of the trend of their outbreak in the field is difficult.[7] Seasonal fluctuation of this pest can be traced by using sex pheromone traps. The forecasting by using traps baited with a synthetic sex pheromone will con-

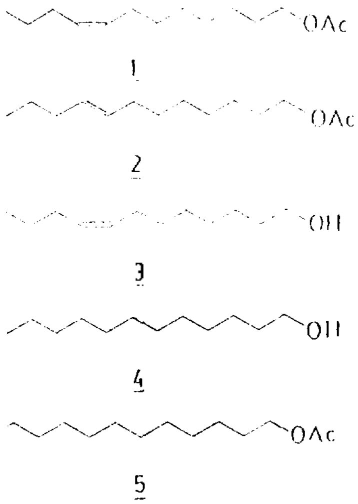


Figure 1.