

Theoretical Study of Ion Pair S_N2 Reactions: Ethyl vs Methyl Reactivities and Extension to Higher Alkyls

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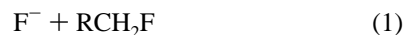
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Abstract: Identity S_N2 reactions of methyl fluoride and chloride with fluoride and chloride ions are compared computationally with the ion pair displacement reactions of lithium fluoride and chloride and of sodium fluoride. The results with the RHF MP2 and B3LYP methods and the 6-31+G* basis set essentially confirm some previous results obtained by RHF and MPn methods. The ion pair reactions proceed via an initial dipole–dipole complex and a cyclic transition structure with highly bent X–C–X bonds that resemble a collection of two cations and two anions. Extension of the calculations to the corresponding ethyl systems gives lower ion pair barriers than methyl, completely different from the corresponding ionic barriers. The bending away of the halogens in the ion pair transition structures reduces steric effects. Analysis of charge distributions shows that in the ionic transition structures the nearby halogens electrostatically inhibit polarization and delocalization of charge. The nonlinear X–C–X bond angle in the ion pair transition structures coupled with the electrostatic influence of the cation permits greater charge polarization and delocalization within the organic moiety and allows the greater stability of ethyl cation compared to methyl to manifest itself. *n*-Propyl, isopropyl, and neopentyl chlorides have lower barriers than ethyl in reaction with lithium chloride but isopropyl and neopentyl chlorides have higher barriers than ethyl toward chloride ion.

Introduction

We recently reported theoretical studies of some ion pair S_N2 reactions.¹ The calculated identity reactions of methyl fluoride and chloride with lithium and sodium fluoride and chloride involve preliminary encounter complexes as found in the many theoretical studies of displacement reactions with ions in the gas phase² except that the ion pair S_N2 analog is a neutral complex between two dipoles instead of a negatively charged ion–dipole complex. The transition structures of these ion pair displacement reactions are characterized by highly bent bonds between carbon and the entering and leaving groups. In the present study these results are extended to correlation effects at the MP2 level and compared with applications of density functional theory (DFT). Two definitions of the charge distributions are evaluated. Finally, the highly bent bonds at the reacting carbon suggest that steric effects might differ for the ion pair reactions compared to reactions with anionic nucleophiles. The reaction barriers are compared for methyl and ethyl substrates. The five sets of reactants studied in the present work are shown with R = H, Me:



Reactions 2 and 4 were extended to *n*-propyl (R = ethyl) and neopentyl (R = *tert*-butyl) chlorides and further compared to the reactions with isopropyl chloride.

Methods

Structures were optimized by using the 6-31+G* basis set at the restricted Hartree–Fock (RHF) level, with second-order Møller–Plesset theory (MP2)³ including all of the electrons (full), and with density functional theory (DFT). The DFT calculations used the Becke hybrid functional (B3LYP)^{4,5} as implemented in the Gaussian 92⁶ and Gaussian 94⁷ series of programs. All stationary points were characterized by normal mode analysis. Charges were calculated by using the topological electron density analysis of Bader,^{8,9} as implemented in AIMPAC, and by the natural population analysis (NPA) of Weinhold.¹⁰

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Table 1. Geometries of the Alkyl Halide and Metal Halide Reactants at RHF, MP2, and DFT Levels with the 6-31+G* Basis Set

	C1-C2			C1-X			\angle XC1C2(H)		
	RHF	MP2	DFT	RHF	MP2	DFT	RHF	MP2	DFT
CH ₃ F				1.371	1.405	1.398	108.5	108.1	108.4
C ₂ H ₅ F	1.513	1.507	1.515	1.377	1.415	1.410	109.6	109.6	109.9
CH ₃ Cl				1.786	1.779	1.806	108.4	108.9	108.5
C ₂ H ₅ Cl	1.517	1.514	1.519	1.800	1.790	1.824	111.5	111.3	111.6
<i>n</i> -PrCl	1.521	1.516	1.524	1.799	1.790	1.822	111.7	111.7	111.8
neoPenCl	1.535	1.527	1.539	1.804	1.792	1.821	114.8	114.2	114.7
<i>i</i> -PrCl	1.520	1.517	1.523	1.816	1.803	1.843	109.3	109.3	109.1
	M-X								
	RHF	MP2	DFT						
LiF	1.575	1.588	1.585						
LiCl	2.066	2.056	2.055						
NaF	1.928	1.945	1.940						

Selected results are summarized in tables and schematic figures in the paper. The complete results in the form of Z-matrices and energies are given in the Supporting Information.

Results and Discussions

It is well-known that the ionic S_N2 reaction in the gas phase contains three reaction steps: (1) two reactants form a reactant ion-dipole complex; (2) the first ion-dipole complex changes to the product ion-dipole complex through a transition structure; and (3) the second ion-dipole complex decomposes into the two products.¹¹ Our previous work¹ shows that the same reaction mechanism applies when an ion pair nucleophile (LiF, LiCl, and NaF) and the methyl halide undergo a corresponding S_N2 reaction in which the metal cation is also involved in the transition structure. The only difference is that the two reactants form a dipole-dipole complex instead of an ion-dipole complex. In the present continuing studies of S_N2 reactions, the nucleophile and the leaving group are identical so that the structures of the first and second complexes (ion-dipole or dipole-dipole) are the same (identity reaction). Even though reactions 1 and 2 with methyl halides have been calculated frequently in the past, they were repeated in the present work in order to provide a direct comparison with the ethyl and ion pair reactions. For convenience the complexes are given numbers 1-5 corresponding to the reactions with **m** = methyl (R = H) and **e** = ethyl (R = CH₃). The corresponding transition structures for reaction are identified with a superscript.[‡]

Reactants. Some geometry data for the reactants are given in Table 1. Inspection of the data in this table reveals that the geometries obtained by the three methods overall are similar. For a given parameter, the small differences obtained among the different methods are largely retained in the complexes and transition structures of the reactions studied. In the rest of this work, the geometries of relevant structures will be given as obtained at the MP2 level. Complete geometries determined by other methods are included in the Supporting Information.

For the series of alkyl chlorides the small variations in the C-Cl bond distance and C-C-Cl angle are consistent with expectations based on the steric requirements of the alkyl group. The C-Cl bond, for example, is shortest (1.779 Å (MP2)) in MeCl and is longest in isopropyl chloride. Furthermore, the bulkier the alkyl group the more the chloride is bent away from the adjacent atom. In going from MeCl to EtCl to neopentyl chloride, for example, the Cl-C-C (H) angle changes from 108.9 to 111.3 to 114.2°. Noteworthy are the similar C-Cl distance and Cl-C-C angle in ethyl and *n*-propyl chlorides.

Ion-Dipole and Dipole-Dipole Complexes. As shown in many previous calculations of the reaction of methyl halides

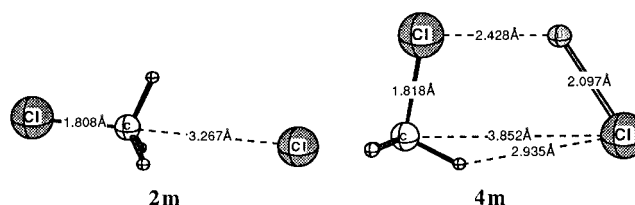


Figure 1. Ion-dipole and dipole-dipole complexes between methyl chloride and Cl⁻ or LiCl (MP2).

with halide ions,¹² the incoming anion in the structure of the ion-dipole complex is at the positive end of the C-X dipole, behind the carbon in a position to form the reaction transition structure (Figure 1). In the ion pair complexes of methyl halides, the two dipoles are oriented at an angle with the metal cation in between both halides (Figure 1).¹ In all of the methyl cases formation of the complexes results in lengthening of the C-X bond by 0.03-0.06 Å with a comparable lengthening of the M-X bond in the ion pair cases. Our MP2 results for **2m**, Figure 1, agree well with previous results¹³ for the same basis set; only small structural changes occur at the MP2 level with different basis sets.

In recent years, there have been several theoretical treatments of reactions of ethyl halides with halide ions.^{13b-19} Many of these studies were primarily concerned with the E2 reaction. Jensen^{13b} and Morokuma²⁰ have computed the ion-dipole complexes for these reactions. These belong to the C_s point group and exhibit features similar to those of the methyl halide complexes. Results from our calculations of these complexes are comparable to those published and are given schematically for ethyl chloride, **2e**, in Figure 2.

A reasonable structure for a precomplex preceding the ion pair transition structure for inversion of ethyl halides is one that belongs to the C_s point group and has the C-X and M-X dipoles aligned in a stabilizing fashion with the positive cation close to the halide of the C-X bond, as shown for EtCl in Figure 2, **4e-C_s**. For the ion pair reaction of ethyl fluoride, this

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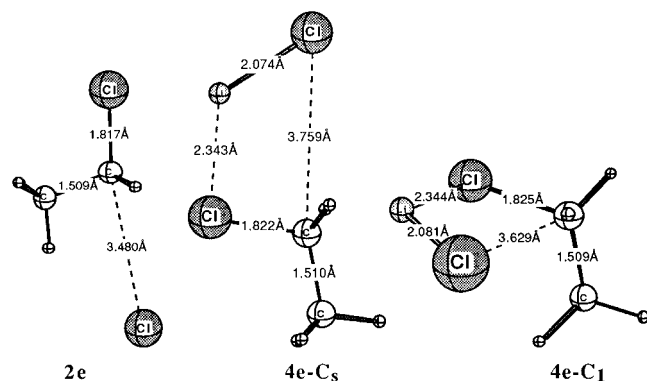


Figure 2. Ion–dipole and dipole–dipole complexes between ethyl chloride and Cl^- or LiCl (MP2).

Table 2. Ion–Dipole and Dipole–Dipole Energies (kcal mol^{-1})

	RHF	MP2(full)	B3LYP
anionic reactions			
$\text{MeF} + \text{F}^- \rightarrow \mathbf{1m}$	-12.84	-13.91	-13.70
$\text{EtF} + \text{F}^- \rightarrow \mathbf{1e}$	-13.62	-15.26	-15.70
$\text{MeCl} + \text{Cl}^- \rightarrow \mathbf{2m}$	-8.88	-9.66	-9.52
$\text{EtCl} + \text{Cl}^- \rightarrow \mathbf{2e}$	-9.42	-11.05	-10.06
ion pair reactions			
$\text{MeF} + \text{LiF} \rightarrow \mathbf{3m}$	-16.05	-18.62	-16.31
$\text{EtF} + \text{LiF} \rightarrow \mathbf{3e-C}_s$	-16.22	-18.91	-16.32
$\text{EtF} + \text{LiF} \rightarrow \mathbf{3e-C}_1$	-16.76	-19.93	-17.27
$\text{MeCl} + \text{LiCl} \rightarrow \mathbf{4m}$	-12.30	-16.21	-13.20
$\text{EtCl} + \text{LiCl} \rightarrow \mathbf{4e-C}_s$	-12.98	-16.47	-13.42
$\text{EtCl} + \text{LiCl} \rightarrow \mathbf{4e-C}_1$	-13.30	-17.17	-14.12
$\text{MeF} + \text{NaF} \rightarrow \mathbf{5m}$	-13.68	-15.67	-14.45
$\text{EtF} + \text{NaF} \rightarrow \mathbf{5e-C}_s$	-12.93	-14.86	-9.62
$\text{EtF} + \text{NaF} \rightarrow \mathbf{5e-C}_1$	-14.00	-16.45	-14.77

complex, $\mathbf{3e-C}_s$, is not a minimum at the HF nor the MP2 energy surfaces, but is instead a species having one imaginary frequency ($31i$ (HF) or $25i$ cm^{-1} (MP2)) corresponding to movement of the LiF fragment out of the molecular plane of symmetry. Relaxation of all symmetry constraints in the geometry optimization leads to $\mathbf{3e-C}_1$ in which LiF is bound to EtF laterally (as shown for EtCl in Figure 2, $\mathbf{4e-C}_1$). At all computational levels $\mathbf{3e-C}_1$ is 0.5 – 1.0 kcal mol^{-1} more stable than $\mathbf{3e-C}_s$. The same phenomenon is also observed for $\mathbf{4e}$. In this case the energy surface is flatter than for $\mathbf{3e}$. The imaginary frequency for $\mathbf{4e-C}_s$ was obtained only at the HF level, and has a small magnitude ($6i$ cm^{-1}). The energy of the $\mathbf{4e-C}_1$ complexes is only 0.3 – 0.7 kcal mol^{-1} lower in energy than that of $\mathbf{4e-C}_s$.

Reaction energies computed for formation of the ion–dipole and dipole–dipole complexes are given in Table 2. When methyl (ethyl) fluoride and fluoride anion form their respective ion–dipole complexes, 12.84 (13.62) kcal mol^{-1} are released (RHF). Formation of the dipole–dipole complex with LiF , however, is more exothermic; the stabilization energy is now 16.05 (16.96) kcal mol^{-1} . The difference arises from the totally different structures of the complexes. The complexes with halide ion are all of the ion–dipole type with the halide ion behind carbon and at the positive end of the C-X bond dipole. The complexes with the metal halide are of the dipole–dipole type with the metal cation close to the halide of the C-X bond. The coordination of lithium cation to fluoride ion and to the alkyl fluoride lone pairs provides a dipole–dipole distance that is effectively much less than the effective ion–dipole distance in $\mathbf{1}$. Similarly, for reaction 2 formation of the complex between the methyl (ethyl) chloride and chloride anion is exothermic by 8.88 (9.42) kcal mol^{-1} ; the stabilization energy for forming the dipole–dipole complex between LiCl and methyl (ethyl) chloride is 12.30 (13.30) kcal mol^{-1} . Replacing LiF by NaF results in a decrease in the stabilization energy of the dipole–dipole complex with methyl (ethyl) fluoride by 2.37 (2.76) kcal

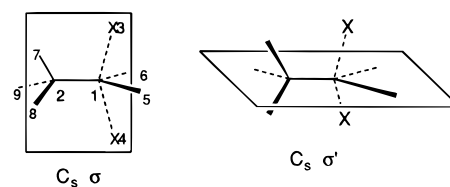


Figure 3. C_s conformations for $\mathbf{1e}^+$ and $\mathbf{2e}^+$. The σ plane on the left is the plane of the paper and the two halides X3 and X4 are not equivalent. The σ' plane on the right is the methylene plane and the two X groups are equivalent. The transition structures have the $C_s \sigma$ structure.

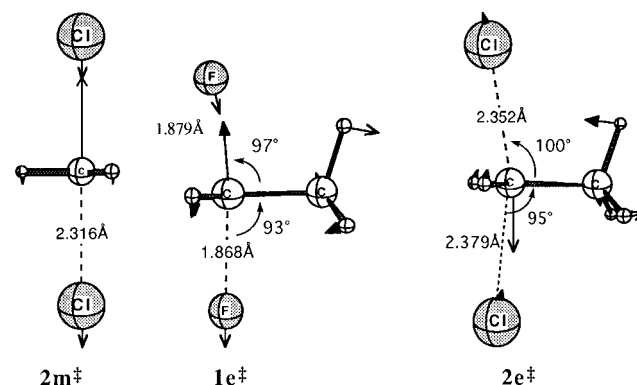


Figure 4. Transition structure and motion in the ionic S_N2 reactions (MP2). The ethyl structures show a tilting motion of the methyl group but not rotation.

mol^{-1} ; this is the expected result since the large sodium cation increases the effective dipole–dipole distance. The complexation energies for all ion–dipole and dipole–dipole complexes at the MP2 level are more exothermic than at RHF. The differences in the energies of complexation between the methyl and ethyl systems are small (ranging from -0.81 to 1.39 kcal mol^{-1} at the MP2 level), and consistent with the comparable polarity of the C-X bond in methyl and ethyl halides.

Ionic Transition Structures. It might be assumed that the transition structure for an identity reaction would have a mirror plane that makes both entering and leaving groups equivalent. But that is not the case for $\mathbf{1e}^+$ and $\mathbf{2e}^+$. The mirror plane in the actual transition structure contains both halogens and is symbolized in Figure 3 as the structure on the left with the σ plane shown. In both structures the entering halide remains eclipsed to one hydrogen of the methyl group and its bond to the central carbon is actually shorter than that of the leaving halide. This type of structure with non-equivalent halides has been reported by others at varying basis set levels,^{13b,15,16,20} including the high-level calculations of Gronert.¹⁹ The principle of microscopic reversibility requires that there be an equivalent transition structure with the entering and leaving groups exchanged. Jensen^{13b} also pointed out the necessity for two such structures. Remarkably, the two transition structures are separated not by a minimum in the potential energy surface (PES) but by a second-order saddle point. The normal mode corresponding to the reaction coordinate has a' symmetry, and does not include (*vide infra*) any motion for rotation of the methyl group. As the system progresses along the reaction path from the ion–dipole complex the entering halide remains eclipsed to one methyl hydrogen. If the reaction were to continue along this path it would then lead to an eclipsed structure of the product. Transition to the other transition structure requires rotation of the methyl substituent, a motion that is not part of the lost vibration of reaction! The reaction motions in $\mathbf{1e}^+$ and $\mathbf{2e}^+$ are shown in Figure 4. Note especially that the methyl hydrogens do move but that that motion retains the σ symmetry plane. The second-order saddle point is only 0.08 kcal mol^{-1} higher in energy than the transition structures,

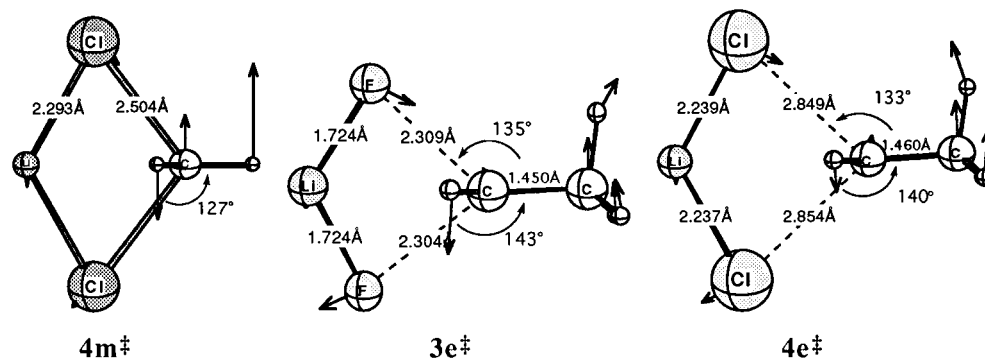


Figure 5. Transition structures and motion in the ion pair S_N2 reactions (MP2).

and one of the imaginary frequencies is that for methyl group rotation. This saddle point has the C_s σ' structure shown on the left of Figure 3 where the mirror plane now is a reflection plane for the two halides that are now equivalent.

We interpret this result as follows. As the system approaches the transition structure the separate rotation of the methyl group, a motion that is one of the normal modes of the system and remains included in its partition function, becomes progressively more facile. A barrier of only 0.08 kcal mol⁻¹ means that the methyl group is effectively freely rotating at this point. Somewhere in the vicinity of the transition structure the system crosses over to the other pathway by rotation of the methyl group and proceeds to the normal product.

It is possible, of course, that higher level calculations would change this result; calculation of a number of points in the PES near the transition structures shows that the PES is rather flat in this region. Nevertheless, Jensen has reported similar transition structures with non-equivalent halides also for reactions of chloride ion with isobutyl, *t*-butyl and neopentyl chlorides. Thus, this type of result may not only be real but may also not be rare for reactions.

Figure 4 also shows that both transition structures have a larger $\angle XCC$ for the incoming X1 halide than for X2. A major factor is probably the repulsion between the halide and the eclipsed hydrogen—a steric effect. The deviation of the X—C—X bond angle from 180° together with the longer C—X distances have been associated previously with steric effects in the S_N2 reaction.^{13b,17,18}

Ion Pair Transition Structures. The MP2 geometries for the ion pair transition structures of MeCl (**4m[‡]**) and the ethyl halides (**3e[‡]** and **4e[‡]**) are displayed in Figure 5. As discussed previously for the reactions of methyl halide,¹ a distinguishing feature of the ion pair transition structures is a large deformation of the XCX angle compared to that in the ionic reactions (Figure 4). This feature is also present in all of the ethyl ion pair reactions. As in the case of the ionic reactions, the ion pair transition structures for ethyl halides have two inequivalent halides contained in a molecular plane of symmetry. The normal modes associated with these reactions have σ' symmetry and do not involve rotation of the methyl group. In the ion pair geometries, however, the halogen staggered with the methyl group has a longer XC bond and a greater XCC angle than the eclipsed halogen.

Reaction Barriers. Classical barrier heights (ΔE^\ddagger) for the ionic and ion-pair S_N2 reactions computed for transformation from separated reactants to transition structures are summarized in Table 3. It is found that ΔE^\ddagger values for **1m[‡]** and **1e[‡]** are 5.69 and 9.21 kcal mol⁻¹. There are significant reductions in ΔE when electron correlation is taken into account. The differences in ΔE^\ddagger values between the RHF level and MP2 (DFT) levels are 6.67 (9.96) and 7.03 (9.96) kcal mol⁻¹ for **1m[‡]** and **1e[‡]**, respectively. Relative to the RHF level, ΔE^\ddagger

Table 3. Reaction Barriers^a Calculated for the Ionic and Ion Pair Reactions at RHF, MP2(full), and B3LYP Levels with the 6-31+G* Basis Set

	RHF	MP2(full)	B3LYP
anionic reactions			
MeF + F ⁻ → 1m[‡]	5.69	-0.98	-4.27
EtF + F ⁻ → 1e[‡]	9.21	2.19	-0.74
MeCl + Cl ⁻ → 2m[‡]	6.59	7.68	-0.85
EtCl + Cl ⁻ → 2e[‡]	9.18	11.10	2.77
<i>n</i> -PrCl + Cl ⁻ → 2(<i>n</i> -PrCl) [‡]	8.65	9.71	2.16
neoPeCl + Cl ⁻ → 2(neoPeCl) [‡]	16.76	17.18	8.92
<i>i</i> -PrCl + Cl ⁻ → 2(<i>i</i> -PrCl) [‡]	10.06	13.99	5.29
ion pair reactions			
MeF + LiF → 3m[‡]	50.85	49.14	42.49
EtF + LiF → 3e[‡]	38.88	37.93	32.43
MeF + NaF → 5m[‡]	49.85	39.36	36.36
EtF + NaF → 5e[‡]	40.95	34.35	30.72
MeCl + LiCl → 4m[‡]	36.91	39.92	29.42
EtCl + LiCl → 4e[‡]	23.19	30.01	19.67
<i>n</i> -PrCl + LiCl → 2(<i>n</i> -PrCl) [‡]	22.13	29.26	18.75
neoPeCl + LiCl → 4(neoPeCl) [‡]	19.87	28.14	17.85
<i>i</i> -PrCl + LiCl → 4(<i>i</i> -PrCl) [‡]	12.68	23.50	15.10

^a $\Delta E^\ddagger = E(\text{transition structure}) - E(\text{separate reactants})$.

values increase by 1.08 and 1.92 kcal mol⁻¹ at the MP2 level but decrease by 7.44 and 6.41 kcal mol⁻¹ at DFT level for **2m[‡]** and **2e[‡]**.

The ΔE^\ddagger values at the B3LYP level for **3m[‡]**–**5m[‡]** and for **3e[‡]**–**5e[‡]** are always lower than those at the RHF and MP2 levels, and the differences between the ΔE^\ddagger values at the RHF and DFT levels vary over a wide range from 3.52 to 13.49 kcal mol⁻¹. It is found that the relative energies at the MP2 level are not consistently lower than those at the RHF level for all of the transition structures. ΔE^\ddagger values for **4m[‡]** and **4e[‡]** at the MP2 level are found to be higher than those at RHF by 3.01 and 6.82 kcal mol⁻¹, respectively. For **3m[‡]** and **3e[‡]**, the ΔE^\ddagger values at the RHF and MP2 levels are similar; the differences are 1.71 and 0.95 kcal mol⁻¹, respectively. There are large changes in ΔE^\ddagger values between the RHF and MP2 levels for **5m[‡]** and **5e[‡]**; the differences are 10.49 and 6.60 kcal mol⁻¹, respectively. Complete structure and energy details are given in the Supporting Information. The occasional large differences in transition structure properties between MP2 and B3LYP suggest that the latter may not always be reliable for transition structures; such differences have been observed previously.¹⁹

Despite the variations in energy changes among the different theoretical levels, some consistent energy patterns emerge. For example, changing the halogen from F to Cl gives a reduction in the energy difference between reactants and transition structures for both methyl and ethyl and by comparable amounts at all levels. The ΔE^\ddagger values for **3m[‡]** (**3e[‡]**) and **4m[‡]** (**4e[‡]**) are lower by 13.94 (15.69), 9.22 (7.92), and 13.07 (12.76) kcal mol⁻¹ at the RHF, MP2, and B3LYP levels, respectively. Comparison of **3m[‡]** (**3e[‡]**) with **5m[‡]** (**5e[‡]**) shows that replacement of lithium by sodium has a generally smaller effect on the

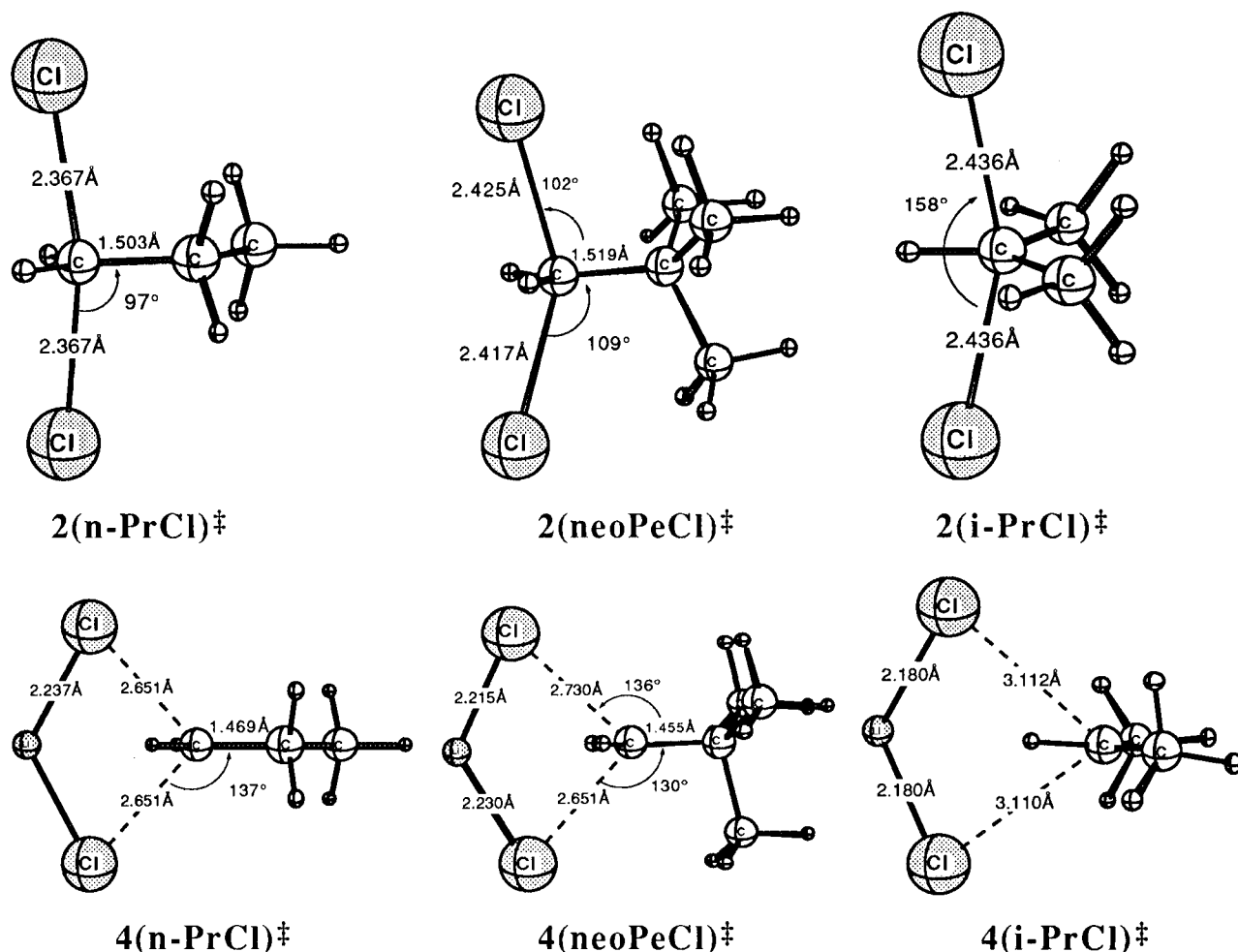


Figure 6. Transition structures for anionic and ion pair S_N2 reactions of n -propyl, neopropyl, and isopropyl chlorides with Cl^- and with $LiCl$ (MP2).

transition energy; the $\Delta\Delta E^\ddagger$ values are 1.28 (−2.14), 9.78 (3.58), and 6.13 (1.71) kcal mol $^{-1}$ at the RHF, MP2, and B3LYP levels, respectively. Thus, a larger anion has a greater effect than a larger cation on the ion pair S_N2 reaction.

The most remarkable effect, however, is the change at the central carbon from methyl to ethyl. In all cases and at all theoretical levels the reaction barriers in the ion pair reactions are substantially lower for ethyl than for methyl, a complete reversal from the ionic reactions. This conclusion is unchanged whether one considers energy changes from the separated reactants or from the initial dipole–dipole complexes. The effect of changing from methyl to ethyl is almost as great for the reaction of $RCI + LiCl$ as for $RF + LiF$, but the differences are substantially smaller for the $RF + NaF$ reactions. The lithium ion pair reactions involve a much reduced $X-C-X$ angle at the transition structure compared to sodium, and this may be the principal cause of this remarkable reactivity difference. As the cation becomes larger and this angle opens up the system approaches that of the ionic transition structure with its almost linear $X-C-X$ angle. The results further suggest that the bending away of the two halides in the ion pair transition structure reduces the steric effects with the rest of the organic structure; that is, if it were not for steric effects, S_N2 reactions would be generally faster for ethyl than methyl substrates.

The generality of this conclusion was tested by study of the S_N2 reactions of n -propyl, isopropyl, and neopentyl chlorides with chloride ion and with lithium chloride. Anionic and ion pair transition structures optimized at the MP2 level are given in Figure 6, and reaction barriers computed at the HF, MP2, and B3LYP levels are included in Table 3.

The transition structures of the two reactions of n -propyl chloride have the two chlorides equivalent with respect to a plane of symmetry containing the three propyl carbons. The orientation of the ethyl moiety in these geometries is expected to have steric effects on the reaction centers in the transition structure that are comparable to those of the methyl group in the reactions of ethyl chloride. Accordingly, the calculations reveal similar reaction barriers for the reactions of ethyl and n -propyl chlorides. At all computational levels, and for both the ionic and ion-pair reactions, the reaction barriers for the reactions of n -propyl chloride are 0.6–1.4 kcal mol $^{-1}$ lower than the corresponding reactions of ethyl chloride. A similar computational result has been obtained by Morokuma 20 for the anionic case.

An alternative transition structure search within the constraints of the C_s point group such that the two chlorides and the three carbons are coplanar (one chloride is eclipsed with the ethyl fragment) leads to second-order saddle points having one imaginary frequency corresponding to the S_N2 motion (a' symmetry) and another (a'' symmetry) for rotation of the ethyl moiety. For the ion pair transition structure, the energy of the second-order saddle point is computed to be only 0.8–1.0 kcal mol $^{-1}$ greater than the energy of the true transition structure. For the anionic case, however, this species is computed to be 4.2–5.1 kcal mol $^{-1}$ above the transition structure, illustrating clearly the importance of steric effects on the barrier of ionic S_N2 reactions. Bending of the two chlorides away from the alkyl fragment in the ion pair transition structures makes the geometry insensitive to the conformation of the alkyl group. The closer proximity of the chlorides to the alkyl moiety in the ionic transition structure, on the other hand, causes the reaction

Table 4. Natural Population (NPA) and Integrated (IC) Charges of Ionic Transition Structures

atom	$1m^{\ddagger}$					$2m^{\ddagger}$				
	NPA		IC			NPA		IC		
	RHF	MP2	RHF	DFT	MP2	RHF	MP2	RHF	DFT	MP2
C1	-0.029	-0.179	0.470	0.301	0.325	-0.263	-0.488	0.162	0.032	0.026
H2	0.204	0.210	0.084	0.079	0.089	0.251	0.259	0.142	0.116	0.132
X5	-0.792	-0.726	-0.862	-0.769	-0.796	-0.745	-0.645	-0.794	-0.691	-0.710
CH ₃ ^a	0.583	0.451	0.722	0.538	0.592	0.490	0.289	0.588	0.380	0.422
atom	$1e^{\ddagger}$					$2e^{\ddagger}$				
	NPA		IC			NPA		IC		
	RHF	MP2	RHF	DFT	MP2	RHF	MP2	RHF	DFT	MP2
C1	0.155	-0.006	0.399	0.289	0.311	0.016	-0.239	0.115	0.048	0.047
C2	-0.669	-0.713	0.159	0.035	-0.015	-0.715	-0.736	0.131	0.015	-0.033
X3	-0.799	-0.723	-0.867	-0.768	-0.795	-0.765	-0.651	-0.805	-0.692	-0.712
X4	-0.805	-0.725	-0.869	-0.772	-0.795	-0.803	-0.670	-0.832	-0.714	-0.725
H5=H6	0.222	0.230	0.096	0.088	0.101	0.260	0.271	0.153	0.122	0.137
H7	0.240	0.247	0.024	0.037	0.054	0.264	0.261	0.052	0.050	0.066
H8=H9	0.217	0.230	-0.021	0.001	0.019	0.241	0.247	0.015	0.025	0.041
CH ₃ ^a	0.005	0.000	0.141	0.074	0.077	0.031	0.019	0.213	0.115	0.115
CH ₂ ^a	0.599	0.454	0.591	0.465	0.513	0.536	0.303	0.421	0.292	0.321

^a Group charge obtained by summing component carbon and hydrogens.

barrier to become strongly dependent on the orientation of the alkyl group. This difference in rotational barriers at the transition structure might be the reason that *n*-propyl compounds are experimentally generally less reactive than ethyl in S_N2 reactions.

In the transition structures of the reactions of neopentyl chloride, there is no possibility for alleviating the strong steric effects of the *tert*-butyl group by different orientations. Hence, for the ionic S_N2 reactions the calculations indicate a significantly greater reaction barrier for neopentyl chloride than for *n*-PrCl (17.2 and 9.7 kcal mol⁻¹; respectively (MP2)). In the ion pair reactions, however, the calculations predict a reactivity for neopentyl chloride ($\Delta E^{\ddagger} = 23.5$ kcal/mol) significantly greater than that for *n*-PrCl (29.3 kcal mol⁻¹). This result is in line with the conclusion that reaction barriers of ion pair S_N2 reactions tend to be reduced with the increased size of the substituent at the α -position of the reaction center.

All of the above reactions are for substitution at a primary carbon. S_N2 reactions at a secondary carbon provide another system for examination of the role of steric effects on reactivity. Consistent with known reactivity trends, the calculations indicate that the classical barrier height for reaction of Cl⁻ and *i*-PrCl (14.0 kcal mol⁻¹) is about 3 kcal mol⁻¹ greater than that for *n*-PrCl. For the reaction between *i*-PrCl and LiCl, on the other hand, the reaction barrier is 3 kcal mol⁻¹ lower than that of *n*-PrCl.

This conclusion that the ion pair S_N2 reaction can have the reactivity pattern *i*-Pr > neoPen > *n*-Pr > Et > Me has obvious synthesis applications. Indeed, these results provide a new wrinkle in an old reaction. S_N2-type displacement reactions have been used synthetically in organic chemistry for many years, and this reactivity pattern has not been observed; however, ion pairs have rarely been considered for such reactions, and to our knowledge there has not been any systematic study of alkyl substituent effects in such reactions. The present results suggest that such an experimental study could be rewarding. The ion pair displacement reaction is known to have different deuterium isotope effects,²¹ and the ion pair displacement on benzylic compounds has the opposite sign of the Hammett ρ compared to ionic analogs.²²

Electron Density Analysis. These remarkable results were further investigated by a study of charge distributions. Since

many definitions of atomic "charge" within a molecule are available²³ we have compared two, one based on partition of the wave function, the "natural charges" (NPA) of Reed and Weinhold,¹⁰ and the other based on integrations of the electron density function within zero flux boundaries, the "integrated charges" (IC) of Bader.⁹ Integrated charges were obtained for almost all atoms in the transition structures 1^{\ddagger} – 4^{\ddagger} at all three theoretical levels; the present version of our Gaussian program does not provide calculations of NPA by the density functional approach so the NPA values were obtained only for the RHF and MP2 methods. The results are summarized in Table 4 for the ionic transition structures, $1m^{\ddagger}$, $1e^{\ddagger}$, $2m^{\ddagger}$, and $2e^{\ddagger}$, and in Table 5 for the ion pair transition structures, $3m^{\ddagger}$, $3e^{\ddagger}$, $4m^{\ddagger}$, and $4e^{\ddagger}$. The topological properties of the electron density functions are given in Table S1 (Supporting Information).

In an early application of integrated electron populations, Duke and Bader showed years ago that the S_N2 transition structure is highly ionic.²⁴ Their calculation of $1m^{\ddagger}$ gave almost full charges on the two fluorides and on the central methyl group. More recently, Shi and Boyd showed that inclusion of electron correlation at the MP2 level for a number of ionic S_N2 reactions substantially decreases this degree of charge separation at the transition structure but that charges on the entering and leaving groups and on the central methyl group are still high.^{25,26} These results are confirmed in the present work.

The ionic character of these displacement reactions is demonstrated by the high charges on the entering and leaving halides. These are typically about -0.7 to -0.8 by all methods; the high values are given by the RHF methods with MP2 being a little lower—the differences are generally less than 0.1 unit. The distribution of integrated charges is generally quite similar between the DFT and the MP2 methods; differences are rarely more than 0.02 unit for carbon and hydrogen. As measured by the charge on the halide, the NPA charges show the same degree of ionic character as the integrated charges but the distributions between carbon and hydrogen differ. In general, the orbital approach assigns more electron density to carbon than do the topological density distributions. The following discussion emphasizes the MP2 IC values, but the arguments are essentially unchanged if any of the other approaches are applied consis-

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Table 5. Natural Population (NPA) and Integrated (IC) Charges of Ion Pair Transition Structures

atom	$3m^{\ddagger}$					$4m^{\ddagger}$				
	NPA		IC			NPA		IC		
	RHF	MP2	RHF	DFT ^a	MP2	RHF	MP2	RHF	DFT	MP2
C1	0.216	0.002	0.218	0.129	0.156	0.048	-0.317	0.114	-0.023	-0.023
H2	0.176	0.200	0.134	0.107	0.127	0.207	0.243	0.153	0.124	0.141
H3=H4	0.247	0.251	0.270	0.193	0.228	0.250	0.259	0.239	0.161	0.184
X5	-0.925	-0.825	-0.918	-0.774	-0.834	-0.831	-0.661		-0.668	-0.702
M7	0.963	0.945	0.935	0.925	0.929	0.906	0.878		0.913	0.918
CH ₃ ^a	0.886	0.704	0.892	0.622	0.739	0.755	0.444	0.745	0.423	0.486

atom	$3e^{\ddagger}$					$4e^{\ddagger}$				
	NPA		IC			NPA		IC		
	RHF	MP2	RHF	DFT ^a	MP2	RHF	MP2	RHF	DFT	MP2
C1	0.357	0.194		0.123	0.108	0.272	0.013	0.089 ^a	0.014	0.030
C2	-0.808	-0.829	0.044	-0.062	-0.129	-0.806	-0.815	0.060	-0.044	-0.108
X3	-0.940	-0.878		-0.811		-0.871	-0.742	-0.887	-0.728	-0.777
X4	-0.938	-0.875				-0.871	-0.748	-0.890		-0.781
H5=H6	0.260	0.271	0.247	0.191	0.231	0.258	0.268	0.223	0.162	0.193
H7	0.308	0.336	0.109	0.121	0.156	0.313	0.326	0.115	0.113	0.143
H8=H9	0.269	0.283	0.066	0.075	0.103	0.273	0.281	0.073	0.074	0.097
Li10	0.961	0.944	0.933	0.920		0.901	0.870	0.921		0.912
CH ₃ ^a	0.038	0.073	0.285	0.209	0.233	0.053	0.073	0.321	0.217	0.229
CH ₂ ^a	0.877	0.736		0.505	0.570	0.788	0.549	0.535	0.338	0.416

^a Group charge obtained by summing component carbon and hydrogens.

tently. For convenience, Tables 4 and 5 include the total "group charges" on the methyl and methylene groups by adding the contributions of the component atoms.

The high charges suggest that a simple first-order model of the ionic transition structure at methyl, $1m^{\ddagger}$, is that of a triple ion, but although the methyl group in this transition structure has a high net positive charge, it differs greatly from an isolated methyl cation. In the latter, the charge is mostly distributed to the three hydrogens and the central carbon is almost neutral.^{27,28} In $1m^{\ddagger}$, however, the charge is centered mostly on carbon with relatively little distributed to the three hydrogens. This result is readily rationalized by the electrostatic effect of the two nearby fluoride anions; charge delocalization is electrostatically inhibited. Similarly, in $1e^{\ddagger}$, little charge is delocalized to the methyl group; in free ethyl cation hyperconjugation to the methyl group is known to be important.^{27,28} In $2m^{\ddagger}$ and $2e^{\ddagger}$ replacement of fluoride by the larger, more polarizable chlorides has the predictable effect. The anionic charges are now farther away and the carbocation charge is better able to delocalize. The charge on the central methyl group is less on carbon and more on hydrogen; in the ethyl case, more charge has delocalized to the methyl group.

In the ion pair transition structures the organic moieties have more typical carbocation character. The total charge separation is about the same as in the ionic transition structures; the ion pair transition structures approximate a collection of ions that have net neutrality. In the organic moiety more charge has delocalized to the hydrogens in $3m^{\ddagger}$ and $4m^{\ddagger}$ and to the methyl groups in $3e^{\ddagger}$ and $4e^{\ddagger}$. The halogens are pulled away from carbon by the cation, reducing their electrostatic effect, and the charge on lithium cation also promotes more normal polarization and delocalization of charge in the organic fragment.

Conclusion

Structural effects reported previously for RHF calculations on ion pair S_N2 reactions on methyl halides by lithium and sodium halides are confirmed with considerations of electron correlation at the MP2 level and with the B3LYP density functional approach. The initial dipole-dipole complexes have been characterized for identity reactions of methyl and ethyl halides with lithium and sodium halides. The transition structures show highly bent X-C-X bond angles that resemble a collection of two cations and two anions. The ethyl systems have lower reaction barriers than the methyl systems, unlike the ionic reaction analogs. Pulling the halides away from the organic fragment by the cation reduces their steric effect with, for example, the methyl group in the ethyl reaction. Analysis of charge distributions also shows that this distancing of the halides also reduces their electrostatic effect which, combined with that of the alkali cation, permits polarization and delocalization of charge within the organic fragment more like that of the free carbocations. The greater stability of ethyl cation compared to methyl becomes more manifest in the ion pair S_N2 reaction. The reduced steric effects for the ion pair displacement reactions are also found for some larger alkyl groups. These results may be general for organic compounds with substituents in the α and β positions and should be verifiable experimentally.

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Supporting Information Available: Topological properties of electron density distributions (Table S1), summary of computed energies (Table S2), and Z-matrices of all structures (29 pages). See any current masthead page for ordering and Internet access instructions.

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