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Through-Space Charge and Dipolar Effects in Substituted Ethanes and 1,1,1-Trifluoroethanes

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The results of ab initio calculations with the 6-31+G* basis set are reported on over sixty compounds of the type CZ_3CH_2X (Z = H, F) and on a few longer chain-substituted alkanes. Data for the eclipsed conformations with Z = H and both the staggered and eclipsed conformations with Z = F are presented. The charges on the atoms in these molecules are determined with the Atoms in Molecules (AIM) and Natural Population Analysis (NPA) methods of analysis. The charges on the fluorine atoms in the trifluoroethyl derivatives parallel those of the hydrogen atoms of the ethyl derivatives. A potential gradient model for charge variations is presented. In this model, the magnitude of the charge is dictated by a through-space electrostatic interaction that arises from the charges on the atoms of the CH_2X group. The length of the vectors from the atoms in the CH_2X group to the bond critical point of the C−Z (Z = H, F) bond and the angle this vector makes with the C−Z bond are critical parameters. The model is tested in systems in which the charge of the methylene carbon atom can be ignored, as well as more rigorously with inclusion of the charge of the methylene carbon atom. The potential gradient model accounts for a greater positive (negative) charge on the antiperiplanar atom than on the gauche ones (staggered conformer) and on the gauche compared to synperiplanar (eclipsed conformer) for positively (negatively) charged X. The model also gives a rationalization for the change in charge observed on the Z atoms when $X = EH_n{}^q$ is replaced by $X = EF_n{}^q$. Comparisons of antiperiplanar and eclipsed conformers of CH_3CH_2X and CF_3CH_2X show that these conformational changes have little effect on the charges of the atoms in the methylene (CH_2X) fragment.

Introduction

The notion of the charge on an atom in a molecule is central to the structural model that most chemists employ when they think about molecules and reactivity. Although the charge is not an eigenvalue of any quantum mechanical operator[1] until an atomic basin is defined[2] and charge calculations give widely different answers dependent upon the method of analysis,[1,3−8] rationalizations based upon charge are widely used in chemistry.[9,10] For example, in a molecule with a carbon−fluorine bond, it is generally assumed that a partial positive charge resides on the carbon atom and a partial negative charge on the fluorine atom. Relative to the corresponding C−H bond, this polarization influences properties at other sites in the molecule. This type of substituent effect remains an area of intense investigation. Many are particularly concerned with the mechanism—orbital interaction, through-bonds polarization (classical induction), or through-space—by which the perturbation is transmitted.[11−17] Our approach to this mechanistic problem is to investigate how a substituent at a given site in a molecule influences the charge[18] and other quantum mechanical properties[19] at remote sites in the molecule using ab initio calculations.

A portion of our earlier efforts involved the variation in the methyl hydrogen atom charges in CH_3CH_2X. The variations with charged X were accounted for with a simple electrostatic potential (through-space) model. We also discovered that fluorine atoms close to hydrogen atoms of the methyl group cause these hydrogen atoms to become more positive. To understand this last effect and to probe the generality of our conclusions about the distribution of charge in substituted alkanes, we have extended our initial study to a number of eclipsed monosusbstituted ethanes and to staggered and eclipsed monosubstituted 1,1,1-trifluoroethanes. Eclipsed conformers have longer bond lengths than the corresponding staggered conformers[20−23] and have different geometric relationships between the X group and the atoms in the CH_3 or CF_3 group. By extending the original CH_3CH_2X data to include the corresponding eclipsed conformers, we can make further observations regarding through-space charge effects and the proximity effect of fluorine atoms in the X group. The study of monosubstituted 1,1,1-trifluoroethanes allows us to determine if the changes found in the hydrogen atoms of a methyl group are found in other situations. Although fluoroethanes have been extensively studied,[22,24,25] there are, to the best of our knowledge, no systematic reports of charge variation in these species.

Our primary interest is not in establishing the actual charge on the atoms in these molecules (if actual charge is even a meaningful concept). Rather, we are interested in attempting to assess the cause of charge variation as a function of a change of the X group. We will discuss our results in terms of two methods of charge assessment, the topological approach of Bader, the Atoms in Molecules (AIM) method,[26,27] and the Natural Population Analysis (NPA) calculation of Weinhold and co-workers.[28]

Computational Methods

Calculations were performed using Gaussian-94 revisions B.1 and B.2[29] and Gaussian-98 revision A.7[30] on a SGI Power XZ Indigo2 running IRIX 6.2 or on a Dell OptiPlex GX1p machine

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TABLE 1: AIM Charges on Atoms in Substituted Staggered 1,1,1-Trifluoroethanes

X	F_{ap}	F_g	C of CF_3	H of CH_2	C of CH_2	X
F	−0.743	−0.739	2.050	0.063	0.772	−0.727
SO_2F	−0.739	−0.740	2.123	0.113	0.006	−0.135
OH	−0.746	−0.742	2.036	0.025	0.774	−0.630
CF_3	−0.743	−0.741	2.064	0.075	0.184	−0.161
H	−0.748	−0.748	1.992	0.038	0.142	0.038
NH_2	−0.747	−0.751	1.961	0.033	0.627	−0.406
NF_2	−0.742	−0.740	2.073	0.086	0.569	−0.587
SiH_3	−0.748	−0.751	1.990	0.040	−0.590	0.782
SiF_3	−0.745	−0.745	2.035	0.067	−0.675	0.741
CH_3	−0.749	−0.750	1.972	0.020	0.153	0.088
CH_2Li	−0.754	−0.756	1.913	−0.023	0.174	0.229
CH_2F[a]	−0.747	−0.743[b]	1.979	0.048[b]	0.142	0.003
		−0.749		0.033		
CH_2F[c]	−0.746	−0.748	1.992	0.044	0.151	0.012
CH_2^-	−0.765	−0.768	1.805	−0.047	0.189	−0.597
CF_2^-	−0.760	−0.754	1.888	−0.014	0.168	−0.741
BH_3^-	−0.765	−0.763	1.799	−0.048	−0.259	−0.160
BF_3^-	−0.762	−0.755	1.844	−0.021	−0.334	−0.196
$B(OH)_3^-$	−0.764	−0.759[d]	1.767	−0.036[d]	−0.289	−0.201
		−0.762[d]		−0.019[d]		
NH_3^+	−0.727	−0.736	2.156	0.130	0.421	0.361
NF_3^+	−0.721	−0.728	2.274	0.192	0.294	0.228
OH_2^+	−0.724	−0.733	2.193	0.170	0.417	0.242

[a] The fluorine atom is gauche to the C−C bond of the trifluoroethane group. [b] Same side of the plane defined by the three carbons of the molecule as is the fluorine atom of the CH_2F group. [c] The fluorine atom is antiperiplanar to the C−C bond of the trifluoroethane group. [d] The orientation of the hydrogens on the oxygens removes the plane of symmetry from this species.

running Linux, Red Hat Version 6.0 or 7.0. The structures in this study were optimized using the 6-31+G* basis set and all further analyses were carried out using the resulting geometries. We have previously discussed the effects of the basis set choice.[18] All results were obtained using the SCF = Tight and Opt = Tight convergence criteria. Calculations of the eclipsed conformers of CZ_3CH_2X (Z = H, F) were performed by freezing a Z−C−C−X dihedral angle at 0° while all other variables were optimized to minimize the energy. The NPA method, Natural Bonding Orbital Version 3.1,[31−33] was implemented through Link 607 of the Gaussian package. The AIM procedure was performed using the programs EXT94b and PROAIMV[34] as downloaded[35] and compiled on our machines. In some instances, the program PROAIM gave answers that were ridiculous (fluorine atom with a −2 charge, for instance) or in which the sum of the charges on the atoms in the molecule did not reproduce the total charge. In these cases, we applied the PROMEGA option, which is included in the PROAIMV package, and obtained reasonable results.

Results

Atomic Charges in Staggered Monosusbtituted 1,1,1-Trifluoroethanes. The atomic charges generated by the AIM procedure are presented in Table 1 and those from the NPA analysis are listed in Table S1 (Supplementary Information). The data for the staggered CF_3CH_2X charges of the antiperiplanar and gauche trifluoromethyl fluorine atoms show good correlation between the NPA and AIM values, which indicates that they respond to some common factor independent of the method of analysis.

The fluorine atom charges in the charged 1,1,1-trifluoroethanes, X = BH_3^-, $B(OH)_3^-$, BF_3^-, CH_2^-, CF_2^-, NH_3^+, NF_3^+, and OH_2^+, clearly show that the fluorine atoms are sensitive to the charge of the substituent. A useful way of seeing this is to compare the average charge on the fluorine atoms of these species with this average in the neutral compounds, excluding X = CH_2Li which is essentially a solvated carbanion because of the long C−Li bond. The average NPA charge on the antiperiplanar fluorine atoms are −0.457 ± 0.002, −0.412 ± 0.004, and −0.368 ± 0.002 for the negatively charged, neutral, and positively charged molecules, respectively. For the gauche fluorine atoms, the values are −0.434 ± 0.006, −0.411 ± 0.008, and −0.393 ± 0.009, respectively. The AIM data are also similar: antiperiplanar, −0.763 ± 0.002, −0.745 ± 0.003, and −0.724 ± 0.002; and gauche, −0.760 ± 0.005, −0.745 ± 0.005, and −0.732± 0.003. These data show the formal charge on X is the dominant factor determining the magnitude of the fluorine atom charge. Also, it is obvious from the average data (and from individual comparisons such as the change from X = OH to X = OH_2^+) that the antiperiplanar fluorine atom is more sensitive to the formal charge on the X group than are the gauche fluorine atoms.

Close inspection of the standard deviations of the averages given above for the charge types suggest a second feature is important. The standard deviations of the gauche fluorine atoms are significantly larger than are those for the antiperiplanar fluorine atoms. Analysis reveals these distortions are caused by compounds in which X = EH_n^q is replaced by X = EF_n^q, where q is −1, 0, or 1, and E is the atom attached to the methylene carbon. We have six examples of this kind of variation in X. In all cases, with both the AIM and the NPA methods, the charge on the fluorine atoms in the CF_3 group becomes more positive. In the antiperiplanar fluorine atom, these changes are modest, 0.005 (AIM) and 0.002 (NPA) charge units for the NH_2 to NF_2 transformation, for instance. These small values cause the standard deviations of the average charge within any given value of q to be small. On the other hand, the changes in the charge of the gauche fluorine atoms are considerably larger, 0.011 (AIM) and 0.020 (NPA) charge units for the NH_2 to NF_2 comparison, for example. This causes the standard deviation for the gauche fluorine atoms to be considerably larger. We conclude that the gauche fluorine atoms are more affected by the change in X from X = EH_n^q to X = EF_n^q than the antiperiplanar fluorine atoms. Considering that the gauche fluorine atoms are closer to X, this result agrees with our earlier observations of the proximity effect of fluorine atoms in X.[18]

The methylene hydrogen atom charge data are presented in Table 1 and Table S1. The charges of the methylene hydrogen atoms by either method of calculation reflect the charge of X, with positive X more positively charged and negative X more negatively charged. There is no correlation between the NPA and AIM methods of analysis within the neutral X. For instance, the AIM procedure gives the charge of the methylene hydrogen atoms (in both the CH_3 and CF_3 series of compounds) in the order X = F > X = SiH_3 > X = H whereas NPA gives the order X = SiH_3 > X = H > X = F. The two methods of charge analysis show the charge on the methylene carbon atom is roughly correlated. The NPA method of analysis generates charges on the methylene carbon atom that are highly sensitive to the nature of the atom in the X group to which the carbon atom is attached rather than the charge of that group. The AIM data do not follow this pattern as well. The charge of the carbon of the CF_3 group shows no correlation between the AIM and the NPA methods of analysis. In the latter method, this charge is nearly independent of X. On the other hand, the AIM analysis shows the variations in the charge on the CF_3 carbon atom parallel that of the fluorine atom charges, although the latter change is smaller by a factor greater than ten. What is striking about the data in the AIM analysis is the significantly greater

TABLE 2: AIM Charges on Atoms in Substituted Eclipsed 1,1,1-Trifluoroethanes

X	F_{syn}	F_g	C of CF_3	H of CH_2	C of CH_2	X
F	−0.735	−0.745	2.057	0.066	0.767	−0.727
SO_2F	−0.738	−0.739	2.122	0.121	−0.002	−0.135
OH	−0.739	−0.747	2.044	0.029	0.766	−0.627
CF_3	−0.741	−0.744	2.049	0.081	0.168	−0.209
H	−0.749	−0.749	1.990	0.044	0.122	−0.044
NH_2	−0.754	−0.749	1.964	0.039	0.604	−0.398
NF_2	−0.737	−0.743	2.073	0.091	0.563	−0.591
SiH_3	−0.755	−0.749	1.988	0.048	−0.607	0.785
SiF_3	−0.748	−0.745	2.019	0.075	−0.686	0.738
CH_3	−0.752	−0.749	1.977	0.026	0.131	0.088
CH_2Li	−0.759	−0.755	1.914	−0.016	0.154	0.232
CH_2^-	−0.774	−0.765	1.810	−0.038	0.150	−0.592
CF_2^-	−0.750	−0.760	1.887	−0.006	0.152	−0.755
BH_3^-	−0.763	−0.764	1.809	−0.039	−0.289	−0.159
BF_3^-	−0.753	−0.760	1.838	−0.012	−0.356	−0.198
$B(OH)_3^-$	−0.762	−0.763[a] −0.762[a]	1.722	−0.026[a] −0.015[a]	−0.316	−0.174
NH_3^+	−0.740	−0.731	2.167	0.132	0.409	−0.364
NF_3^+	−0.729	−0.725	2.280	0.194	0.290	0.229
OH_2^+	−0.737	−0.728	2.204	0.172	0.408	0.243

[a] The orientation of the hydrogens on the oxygens removes the plane of symmetry from this species.

TABLE 3: AIM Charges on Atoms in Substituted Eclipsed CH_3CH_2X

X	H_{syn}	H_g	C of CH_3	H of CH_2	C of CH_2	X
F	0.029	−0.009	0.063	0.008	0.659	−0.748
SO_2F	0.016	0.023	0.100	0.072	−0.034	−0.271
OH	0.025	−0.018	0.067	−0.031	0.665	−0.657
CF_3	0.016	−0.001	0.071	0.021	0.151	−0.275
H	−0.022	−0.022	0.067	−0.022	0.067	−0.022
NH_2	−0.022	−0.021	0.031	−0.018	0.543	−0.472
NF_2	0.037	−0.003	0.072	0.032	0.483	−0.651
SiH_3	−0.029	−0.014	0.07	−0.01	−0.732	0.741
SiF_3	−0.012	0.000	0.078	0.018	−0.810	0.714
CH_3	−0.023	−0.023	0.052	−0.035	0.102	−0.017
CH_2Li	−0.027	−0.047	0.038	−0.077	0.113	0.125
CH_2^-	−0.047	−0.090	0.002	−0.094	0.114	−0.703
CF_2^-	0.010	−0.075	0.040	−0.068	0.104	−0.874
BH_3^-	−0.040	−0.086	0.039	−0.106	−0.438	−0.172
BF_3^-	−0.023	−0.073	0.052	−0.080	−0.506	−0.217
$B(OH)_3^-$	−0.028	−0.084[a] −0.081[a]	0.054	−0.083[a] −0.097[a]	−0.472	−0.206
NH_3^+	0.013	0.058	0.068	0.075	0.332	0.320
NF_3^+	0.066	0.081	0.090	0.139	0.214	0.186
OH_2^+	0.038	0.069	0.076	0.120	0.293	0.216

[a] The orientation of the hydrogens on the oxygens removes the plane of symmetry from this species.

range of charge expressed by the carbon atom of the CF_3 group compared to that of the CH_3 group in CH_3CH_2X (see below).

Atomic Charges in Eclipsed Monosubstituted 1,1,1-Trifluoroethanes. We extended our study of monosubstituted CF_3-CH_2X to those in an eclipsed geometry. In these compounds, the trifluoromethyl group is rotated such that one C−F bond of the CF_3 group is eclipsed, or synperiplanar, to the C−X bond. In terms of distance from the X group, the gauche fluorine atoms of the eclipsed conformers are intermediate between the antiperiplanar and the gauche of the staggered conformer, whereas the synperiplanar fluorine atom is closer to the X group than any fluorine atom in the staggered conformer. The atomic charges generated by the AIM method are listed in Table 2 and those from the NPA procedure are included in Table S2 (Supplementary Information).

The trifluoromethyl fluorine atom data for the gauche fluorine atoms give a correlation between the NPA and the AIM data with a correlation coefficient of 0.996. The synperiplanar fluorine atom does not correlate as well (correlation coefficient of 0.937). As seen for the staggered conformer, generally a charged X group delocalizes its formal charge onto the peripheral fluorine atoms. We again compare the average values of the charge for the negatively charged, neutral, and positively charged molecules. The values for the gauche fluorine atoms for these three charge types are -0.450 ± 0.003, -0.414 ± 0.006, and -0.378 ± 0.004 (NPA) and -0.762 ± 0.002, -0.746 ± 0.003, and -0.728 ± 0.002 (AIM), respectively. The differences between the charge types are well outside the standard deviation of the values, independent of method. For the synperiplanar fluorine atom, the averages are -0.425 ± 0.008, -0.409 ± 0.010, and -0.402 ± 0.010 (NPA) and -0.760 ± 0.008, -0.745 ± 0.007, and -0.735 ± 0.005 (AIM), respectively. The negatively charged species have the synperiplanar atom clearly more negatively charged, but the positively charged species and the neutral species have overlapping ranges. The difference in the average values for the negative and neutral compounds is greater for the gauche fluorine atoms than for the synperiplanar ones; the gauche fluorine atoms are more sensitive to the charge of the X group, even though they are more remote.

As we noted above in the staggered conformers, the standard deviation of the averages is larger for the synperiplanar fluorine atoms than for the gauche ones. The primary factor causing the deviation is the difference in charge in the CF_3 group when X is changed from X = EH_n^q to X = EF_n^q. Comparison of these types shows that compounds with X = EF_n^q have more positive fluorine atoms in the CF_3 group than those with X = EH_n^q. Also, in almost all cases (X = BH_3^-/BF_3^- in the NPA method is the only exception), the change between X = EH_n^q and X = EF_n^q is larger for the synperiplanar fluorine atom than it is for the gauche fluorine atoms.

Plots of the charge on the methylene hydrogen and carbon atoms, as determined by the two methods of analysis, show behavior similar to that exhibited in the staggered conformer, as do the results for the charge on the carbon atom of the CF_3 group.

Atomic Charges in Eclipsed Monosubstituted Ethanes. We have extended our earlier work[18] on the charge distribution in substituted alkanes by investigating charge variation on the atoms in several eclipsed monosubstituted ethanes. The data for the calculated AIM charges are given in Table 3 and the NPA charges are listed in Table S3 (Supplementary Information). Like the methyl hydrogen atoms in the staggered monosubstituted ethanes, we find a strong relationship (r = 0.996) between the charges on the gauche hydrogen atom calculated by the NPA and AIM procedures of analysis. The correlation for the charge on the synperiplanar hydrogen atoms has r = 0.996.

As we found for the antiperiplanar monosubstituted ethanes and for the 1,1,1-trifluoroethanes described above, the data in Table 3 (Table S3) show positive charge is localized on methyl hydrogen atoms in compounds where X carries formal positive charge. Likewise, negative charge is delocalized onto the methyl hydrogen atoms when X is formally negative. In all instances, we observe the gauche hydrogen atoms are more sensitive than the synperiplanar hydrogen atom to a charge on X. This observation is consistent with those made above for the eclipsed 1,1,1-trifluoroethanes. We also observe the same behavior for the eclipsed substituted ethanes as we do for eclipsed substituted trifluoroethanes when EH_n^q is changed to EF_n^q. For instance, the change from X = NH_3^+ to X = NF_3^+ causes the synperiplanar hydrogen atom to become 0.031 (NPA) or 0.053 (AIM) units more positive whereas the gauche hydrogen atoms become only 0.012 (NPA) or 0.023 (AIM) units more positive.

We find significantly less agreement between the NPA and AIM generated charges for the methyl carbon, methylene carbon, and methylene hydrogen atoms. Both methods of analysis show that positively charged X give methylene hydrogen atom charges that are more positive, and conversely with negative X. There is at best a poor correlation of the compounds with neutral X between the two methods of analysis.

Rotation about the C−C bond of CZ_3CH_2X for a given X moves charge around on the Z atoms of the CZ_3 group, but, remarkably, not across the C−C bond. This is most easily seen by computing the average of the difference between the charge on the CH_3 group upon changing from the staggered to the eclipsed conformer. The values are -0.001 ± 0.002 (AIM) and 0.001 ± 0.005 (NPA). The same average differences for the CF_3 group are -0.003 ± 0.013 (AIM) and -0.003 ± 0.002 (NPA).

Discussion

The data reported above, as well as that published earlier,[18] allow a detailed investigation of the factors that cause variation in charge in the peripheral atoms of ethyl compounds, trifluoroethyl derivatives, and higher homologues. Our approach is to treat the X group as a source of an electrostatic potential that influences, through space, charge at the remote sites. In Section 1, we discuss a qualitative model to account for the effect of charged X on atoms of the trifluoromethyl and methyl groups. The remaining sections use a calculation of the electrostatic potential gradient to obtain a semiquantitative prediction of the charge on the peripheral atoms. In Section 2, we outline our method and discuss a potential difficulty with its application—the role of the methylene carbon atom. We apply the model in Section 3 to some situations in which it is reasonable to believe the role of the methylene carbon atom can be removed from consideration by carefully chosen comparisons. In Sections 4 and 5, we use the model to understand the comparison of $X = EF_n{}^q$ with $X = EH_n{}^q$ compounds and the charges on remote atoms in long chain compounds, respectively. Finally, in Section 6, we plunge forward, ignore our concern for the closeness of the methylene group, and attempt to find the limits to which our through-space model can be stretched.

1. Qualitative Evidence for a Through-Space Perturbation by Charged Substitutents. In Figure 1, we plot the AIM charge of the antiperiplanar fluorine atoms in trifluoroethyl compounds against those of the antiperiplanar hydrogen atoms previously reported for the ethyl compounds.[18] This linear relationship between the two sets of data indicates that the X group perturbs the charge in the same manner, independent of whether the recipient of that perturbation is a hydrogen or a fluorine atom. The slope of this plot ($q_{TFM}\{F_{ap}\} = \{0.217 \pm 0.004\}\ q_{Me}\{H_{ap}\} + \{-0.742 \pm 0.000\}$, $r = 0.998$)[36] shows that the response of a fluorine atom is about one-fifth as large as that of a hydrogen atom. Similarly, for the gauche position, the change in charge on the fluorine atom is about 30% of that of the hydrogen atom ($q_{TFM}\{F_g\} = \{0.290 \pm 0.015\}\ q_{Me}\{H_g\} + \{-0.745 \pm 0.001\}$, $r = 0.974$). The AIM method therefore assigns a much higher polarizability to electrons in a C−H bond.[37,38] This is also demonstrated in a comparison of a CF_3 group with a SiF_3 group: the charge on the fluorine atom is only about 0.14 charge units lower in the latter whereas the hydrogen atom charge decreases from about zero to −0.7 charge units in going from a methyl group to a silyl group. In contrast, the corresponding NPA data show considerably larger slopes ($q_{TFM}\{F_{ap}\} = \{0.74 \pm 0.02\}\ q_{Me}\{H_{ap}\} + \{-0.582 \pm 0.004\}$, $r = 0.994$ and $q_{TFM}\{F_g\} = \{0.80 \pm 0.04\}\ q_{Me}\{H_g\} + \{-0.596 \pm 0.009\}$, $r = 0.978$), reflecting a more similar polarizability for electrons in C−F and C−H bonds.

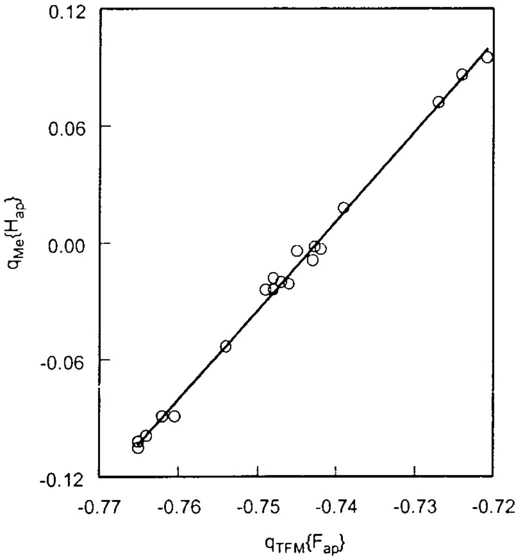

Figure 1. The relationship between the charge on the antiperiplanar hydrogen atom in CH_3CH_2X and the corresponding fluorine atom in CF_3CH_2X. AIM data.

For charged X, we have previously accounted for the charge on remote hydrogen atoms in substituted alkanes with a through-space mechanism.[18] We modeled this effect by determining the potential-energy gradient at the midway point of the C−H bond *along the axis* of the bond. Here, we refine this analysis and apply it to the fluorine atoms of the CF_3 group in substituted trifluoroethanes. Our first change is to assume the pertinent position in the bond for motion of electrons is the critical point of the bond rather than the midway point. This assumption is based on the idea that a change in charge on an atom most likely requires a change in the boundary between that atom and one of its neighbors. The bond critical point defines this boundary. For our qualitative argument, we assume that the sum of the charges on all atoms in X is centered on the E atom in $X = EY_n{}^q$. The charge at E creates the potential-energy gradient at the remote carbon−fluorine bond. The magnitude of this gradient depends on cos θ, where θ is the angle between the vector from E to the bond critical point of the C−F bond and the C to F bond vector, and inversely on the distance between the charge and the critical point. The angular dependence causes the antiperiplanar fluorine atom in the staggered conformers to have a stronger response (greater cos θ) to the charge on X than the gauche fluorine atoms in CF_3CH_2X even though the antiperiplanar fluorine atom is further away from the X group. In the eclipsed conformers, the synperiplanar fluorine atom has an unfavorable cos θ compared to the gauche ones: the gauche fluorine atoms are more negative for negatively charged X. The data in Tables 1 and 2 (Table S1 and S2) support this model for the trifluoroethyl derivatives. A similar result holds for the gauche and synperiplanar hydrogen atoms in eclipsed ethyl derivatives, see Tables 3 and S3.

We noted above that the charge on the carbon atoms of the CF_3 group are, in an AIM analysis, much more sensitive to the change in X than are the fluorine atoms. There is a linear relationship between the charge on the trifluoromethyl carbon atom and the sum of the charge on the three fluorine atoms: if X increases the charge on the fluorine atoms (makes them less negative), the charge on the carbon atom also increases. This relationship holds for all 40 compounds in Tables 1 and 2; the

TABLE 4: Charge, Distance, and Angle Data for the CF_3 Group in Trifluoromethyl Substituted Ammonium Ions[a]

compound	$q_{TFM}\{C\}$	R_{N-bcp},[b] Å	θ[c]	$q_{TFM}\{F_{ap}\}$	$q_{TFM}\{F_g\}$
$CF_3CH_2NH_3^+$	2.156	1.86	50°	−0.727	−0.736
$CF_3(CH_2)_2NH_3^+$	2.105	3.09	27°	−0.736	−0.741
$CF_3(CH_2)_4NH_3^+$	2.034	5.61	30°	−0.742	−0.746
$CF_3(CH_2)_4NH_3^{+}$[d]	2.007	5.19	74°	−0.741[e]	[f]
$CF_3(CH_2)_4CH_3$	1.974			−0.749	−0.750

[a] Compounds have C_s symmetry except as noted; AIM charges. [b] The distance between the nitrogen atom and the bond critical point of the $C_{TFM}-C_{n-1}$ bond. [c] The angle between a vector from the nitrogen to the bond critical point of the $C_{TFM}-C_{n-1}$ bond. [d] Conformer in which the C_2–C_3–C_4–C_5 dihedral angle is 64.1°. [e] Antiperiplanar to C_3. [f] The two nonequivalent fluorine atoms have charges of −0.748 (5.675 Å from N) and −0.753 (5.003 Å from N).

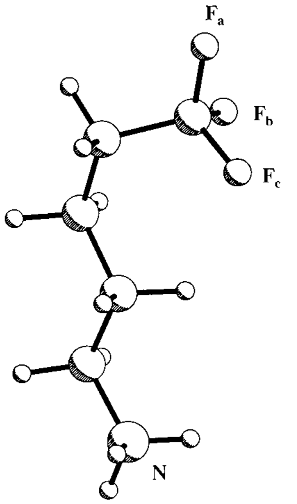

Figure 2. Optimized geometry of the twisted $CF_3(CH_2)_4NH_3^+$ ion at the 6-31+G* level.

linear fit, $q_{TFM}\{C\} = (4.09 \pm 0.14)\, \Sigma q_{TFM}\{F\} + (11.2 \pm 0.3)$, r=0.979, shows the variation in carbon atom charge is four times that of the sum of the fluorine atom charges. This variation in charge on the carbon atom in the trifluoroethyl compounds is in contrast to the charge of the carbon atom of the methyl group of CH_3CH_2X, which shows little variation with X. We have investigated the distance and angular dependence of the charge of the carbon atoms in compounds with X = NH_3^+, see Table 4. The charge on the trifluoromethyl carbon atom decreases from 2.156 to 2.034 as the number of methylene groups separating the CF_3 group from the ammonium group increases from one to four. From the data given in the table, clearly this decrease is mostly due to an increase in the distance between the nitrogen center and the bond critical point of the $C_{TFM}-C_{n-1}$ bond.[39] We believe this bond is the critical one as the source of charge variation is the rest of the molecule, not the fluorine atoms in the CF_3 group. To test our model further, we have examined a conformer of $CF_3(CH_2)_4NH_3^+$ in which the C_2–C_3–C_4–C_5 dihedral angle[39] was set at 60° (minimized value of 64.1°). In this conformer, see Figure 2, the carbon atom of the CF_3 group is closer to the nitrogen atom than it is in the C_s conformer, but the value of θ is considerably less favorable. In our model, the small value of cos θ diminishes the effect of the positive charge. As a consequence, the charge on this carbon atom is less positive; it is decreased toward the value characteristic of a CF_3 group in the absence of an ammonium group, as shown by the last entry in Table 4. This example stresses the importance of the angle between the bond vector and the vector from the approximate center of charge to the bond critical point. This treatment is equivalent to the one that we used to understand the position of the bond critical point in C−C bonds in charged, substituted alkanes.[19]

2. The Potential-Gradient Model. In the qualitative analysis presented above for X = NH_3^+, we assumed the positive charge was centered at the nitrogen atom. In fact, chemical intuition and our calculations show that the nitrogen center is charged negatively in this group, a rather disparaging situation. Clearly, a more reasonable model should exist. We explore here a through-space model to achieve a semiquantitative accounting of the charge variation on remote atoms. Our general model is similar to the classical treatment of Kirkwood and Westheimer,[40−42] and aspects of it have been used in models to predict energy changes by Topsom[43,44] and others.[45,46] We also call attention to earlier studies of electrostatic models in hydrocarbon systems.[47,48] We postulate that a potential gradient is set up at the bond critical point in the C−Z (Z = H, F) bond by the charges on other atoms in the molecule. This potential gradient causes the electron density at the bond critical point in the remote bonds to shift. The gradient, γ_A, is determined by multiplying the charge on an atom A, q_A, by the cosine of the angle made by the vector from the atom to the bond critical point and the bond vector from C to Z and dividing by the distance between the atom and the bond critical point, r_{A-bcp}. The net potential gradient, γ, is the sum of these terms over the pertinent atoms, A, in the molecule:

$$\gamma = \sum_{A} \frac{q_A \cos(\theta)}{r_{A-bcp}}$$

We assume the charge at Z will be proportional to the value of γ.[49] In our tabulated values and in all figures, the γ values are expressed in atomic units of distance.

In principle, this calculation is straightforward. The only difficulty lies in the concept of the "pertinent" atoms. Examination of the compounds listed in Table 3 and in our earlier work[18] shows that the CH_2X group on CH_3CH_2X carries a charge that seems intuitively reasonable: close to neutral when X is neutral and substantially positive or negative (order of magnitude of 0.8 charge units) when X is positive or negative, respectively. A similar result is seen in the trifluoroethyl derivatives, although the CH_2X group is more positive in this case, reflecting the high ionization energy of the fluorine atoms. From this examination, clearly the charge on the methylene carbon atom is important in achieving these "reasonable" values. It therefore appears that we must include the methylene carbon atom in the sum to determine γ. Yet this atom is so close to the methyl (trifluoromethyl) group—the center of our focus—that we are uncertain if orbital and through-bond inductive effects are absent. To nullify this concern, we first attempt to examine the difference in pairs of compounds in which the methylene carbon atom has a similar charge.

3. Comparisons Insensitive to Methylene Carbon Atom Charge. We have previously observed that the charge on the methylene carbon atom is approximately the same when two X = EY_n groups of differing Y but the same E are compared.[18] If we assume that in such a comparison, the varying effects of the bonding interactions, and the through-space contributions to γ, of the methylene carbon atoms are equal, then the pertinent atoms in the calculation of γ are only those in the X group. We use this approximation to examine the methylene hydrogen atom charges as Y is varied with constant E. We have calculated the γ value at the methylene hydrogen atoms for all atoms in the X group where X = CF_3, CF_2H, and CFH_2, with the fluorine atom both antiperiplanar and gauche to the C_1–C_2 bond.[39] From

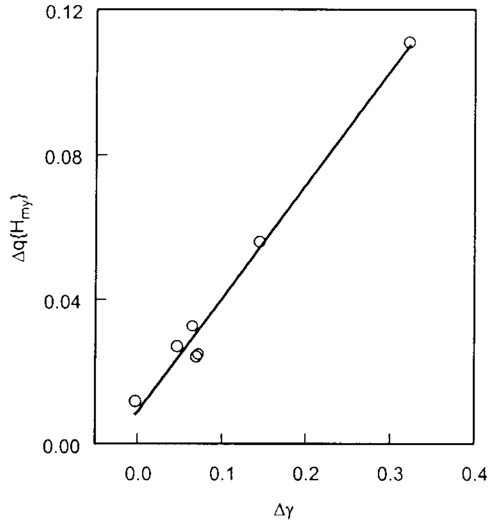

Figure 3. The charge difference of the methylene hydrogen atoms between X = EF_nH_{3-n} and X = EH_n versus the corresponding calculated difference in the potential gradient, $\Delta\gamma$. The points, reading from largest Δq to smallest are $CF_3CH_2CF_3$ compared to propane; X = CF_3; X = CF_2H; X = SiF_3; X = CFH_2, with the F antiperiplanar to the methyl group; X = CFH_2 with the F gauche to the CH_3 group, hydrogen atom closest to the fluorine atom; and the same molecule, methylene hydrogen atom furthest from the fluorine atom. The AIM method was used.

these values, we subtract the calculated γ for X = CH_3. We compare these values of $\Delta\gamma$ to the difference in charge, Δq, of the methylene hydrogen atoms upon the same substitution. In addition, we have determined the $\Delta\gamma$ and Δq for SiF_3/SiH_3 and for 1,1,1,3,3,3-hexafluoropropane compared to propane. The raw data are given in Tables S4 (AIM) and S5 (NPA) of Supplementary Information. A plot of the appropriate comparisons is given in Figure 3, where the AIM data are used. The agreement is reasonable, as is a similar treatment using the NPA method.[50]

Our model requires that Δq for the substitution of a CF_3 group for a CH_3 group is independent of the rest of the molecule. That this is true is shown by a plot of the charge on the methylene hydrogen atoms in CH_3CH_2X versus the charge on those atoms in CF_3CH_2X: $q_{TFM}\{H_{my}\} = \{0.96 \pm 0.01\}\, q_{Me}\{H_{my}\} + \{0.055 \pm 0.001\}$, $r = 0.999$ (AIM). A similar result holds for the NPA data. It is also enlightening to examine the components of γ to understand what effects dominate the calculated values. The origin of the large positive $\Delta\gamma$ on the methylene hydrogen of X = CF_3 is the carbon atom of the CF_3 group. This positive $\Delta\gamma$ comes about from the large charge (1.97 charge units, AIM), small separation distance (3.45 Å), and reasonably favorable θ value (52°) of this carbon atom. This positive contribution to $\Delta\gamma$ is only partially balanced by the fluorine atom on the same side of the symmetry plane of the molecule as the hydrogen atom, which is considerably further away (4.58 Å) and carries a negative charge smaller in magnitude than the positive charge on the carbon atom. This positive $\Delta\gamma$ leads to the positive Δq. In the comparison of SiF_3/SiH_3, the similarity of the charges on the various atoms in SiH_3 with those in SiF_3 keeps $\Delta\gamma$ small.

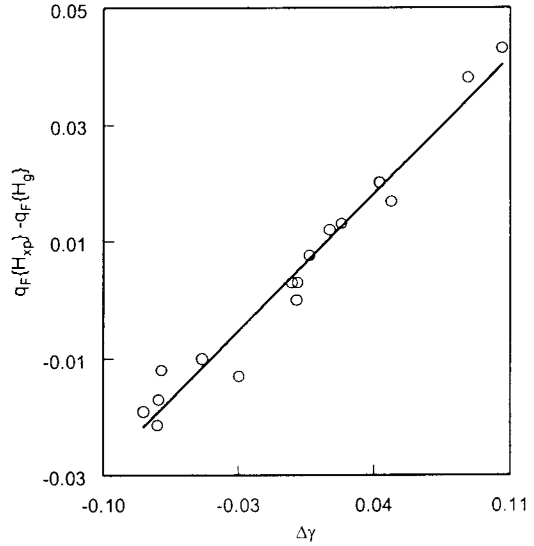

Figure 4. The charge on the antiperiplanar (or synperiplanar) atom minus that on the gauche atom of CH_3CH_2X versus the corresponding differences in potential gradient, γ. AIM data. Reading from the left, with eclipsed conformers indicated by an "e", X is OH; CH_2F, F gauche to CH_3 group, gauche hydrogen atom closest to fluorine atom; CF_2H; F; CF_3; CH_2Li; e-CH_3; H; CH_3; CH_2F, F gauche to CH_3 group, gauche hydrogen furthest from fluorine; CF_2H, with the H atom eclipsed with the C−C bond; CH_2F, F antiperiplanar to the CH_3-methylene carbon bond; e-CH_2Li; e-CF_3; e−F; e-OH.

The effect of the methylene carbon atom may be essentially nullified in a comparison of the antiperiplanar and gauche hydrogen atoms in staggered compounds and in a similar comparison of the synperiplanar and gauche hydrogen atoms in the eclipsed conformers. The difference in γ between the antiperiplanar (synperiplanar) and gauche positions is approximately independent of the charge on the methylene carbon atom as the carbon atom to critical point distance and the values of cos θ are about the same for each of these hydrogen atoms. There is an uncompensated difference in the value of $\Delta\gamma$ because of the methylene hydrogen atoms. In the AIM method, however, the charge on these hydrogen atoms is small and they do not contribute much to γ. When we plot values of $q_{Me}\{H_{ap}\} - q_{Me}\{H_g\}$ and $q_{Me}\{H_{syp}\} - q_{Me}\{H_g\}$ versus $\Delta\gamma$, calculated with all atoms of the CH_2X group included, for all of the compounds that we have studied, we get a plot with considerable scatter ($r = 0.83$). Nevertheless, close inspection of these data shows that the scatter is caused by comparison of compounds of different types. If we plot only the neutral compounds, X = EY_n, where E is a first-row element, we get a straight line ($r = 0.975$). This plot is even better if the two points for X = NY_2 are removed. The data are presented in Figure 4; the line is given by $\{q_F\{H_{xp}\} - q_F\{H_g\}\} = \{0.33 \pm 0.02\}\, \Delta\gamma + \{0.005 \pm 0.001\}$, $r = 0.983$. We believe the NY_2 points are unreliable because we are unable to account for the lone pair of electrons in our point-charge model. Two additional plots result from consideration of all the data. For neutral compounds where E is a second-row element, we find a reasonable plot, $\{q_S\{H_{xp}\} - q_S\{H_g\}\} = (0.11 \pm 0.01)\, \Delta\gamma - (0.005 \pm 0.001)$, $r = 0.962$. The corresponding plot for the charged materials has a somewhat poorer correlation coefficient, $\{q_Q\{H_{xp}\} - q_Q\{H_g\}\} = (0.62 \pm 0.09)\, \Delta\gamma + (0.007 \pm 0.006)$, $r = 0.884$. We address the issue of the need for three different plots in Section 6.

In the NPA data, the charges on the methylene hydrogen atoms are relatively large. Nevertheless, plots of the difference in charge versus the difference in γ calculated from NPA charges show similar straight line relationships. The slope for charged compounds is greater than that of the first-row compounds, which is greater than that of the second-row compounds, as found for the AIM data. As expected, given the linear relationship between the charge of the fluorine atoms in the trifluoromethyl group and the hydrogen atoms in the methyl group, there are also reasonable relationships between the difference in charge of the antiperiplanar (synperiplanar) and gauche fluorine atoms and the calculated values of $\Delta\gamma$ for the trifluoroethyl systems. The scatter is somewhat higher in this case because of the small differences in fluorine atom charges.

How do the various atoms contribute to γ? The value of $\Delta\gamma$ for CF_3 is negative. The carbon atom of the CF_3 group contributes 0.29 electron bohr^{-1} to γ of the antiperiplanar hydrogen atom, over twice as much as it does to the gauche one. This occurs even though the carbon atom is further away from the former because of the significantly more favorable θ value for the antiperiplanar hydrogen atom (30°) compared to that for the gauche (72°). All three fluorine atoms are at reasonably favorable angles to the antiperiplanar hydrogen atom and nearly completely compensate for the effect of the carbon atom by generating a contribution to γ of -0.27 electron bohr^{-1}. The C$-$H bond of the gauche hydrogen atom is much closer to perpendicular to the vectors from the fluorine atoms, which lowers the total γ for these fluorine atoms to -0.06 electron bohr^{-1}, thereby allowing the effect of the carbon atom to dominate at the gauche hydrogen atom. This makes $\gamma_{ap} - \gamma_g$ negative. The most positive values of $\Delta\gamma$ are those of eclipsed X = F and X = OH. For the former, the fluorine atom contributes little to the synperiplanar hydrogen because the θ value is 87°. Thus, both kinds of hydrogen atoms have positive contributions from the methylene carbon atom, but only the gauche hydrogen atoms have corresponding negative values from the fluorine atom. Accordingly, $\gamma_{syn} - \gamma_g$ is very positive.

4. The EH_n/EF_n Replacement: A Through-Space Dipolar Effect. Previously, we reported[18] that X groups containing fluorine atoms within about 2.7 Å of hydrogen atoms on the methyl group in CH_3CH_2X cause those hydrogen atoms to be more positively charged. This effect is also present for the fluorine atoms of the trifluoroethyl compounds. The Z atoms in the CZ_3 group of staggered or eclisped CZ_3CH_2X become more positive when $X = EY_n{}^q$ is changed from Y = H to Y = F, but the gauche atoms are influenced more than the antiperiplanar ones in the staggered conformer, and the synperiplanar are influenced more than the gauche in the eclipsed conformer. These observations are true for every pair, $EH_n{}^q/EF_n{}^q$, independent of n or q, for both Z = H and Z = F. Although the magnitude of the changes in charge are small, especially with Z = F, the generality is impressive. In this section, we use the potential-gradient model to understand this phenomenon.

When this feature was originally observed for Z = H, it was thought that it might be a specific interaction between the fluorine atoms in X and the hydrogen atoms in the methyl group,[51,52] but the observation of a similar phenomenon for Z = F requires an explanation general enough for both Z's. We suggest a dipolar interaction involving the E$-$F bond is responsible. One method of dealing with this interaction would be to use the classical dipole/dipole interaction equation.[53,54] Given that we have calculated charges on all the atoms of the CH_2X group, it appears more straightforward to calculate the through-space potential gradient of each atom in the CH_2X group and to compare the γ for an $X = EF_n$ group with that for an $X = EH_n$ group. This comparison removes most of the effect of the methylene carbon atom, as the charge on this atom is mostly determined by the nature of E and not by the ligands attached to it,[18] and the distance and θ values of a methylene carbon atom are about the same at the methyl hydrogen atoms.

We first consider the neutral CH_3CH_2X compounds. There are eight neutral compounds in which an EH_n group is replaced by an $EF_nH_{(3-n)}$ group: staggered and eclipsed CF_3 and SiF_3, staggered CHF_2, and staggered CH_2F with the fluorine atom antiperiplanar or gauche to the C_1–C_2 bond.[39] We have not considered the NH_2/NF_2 pair for reasons given above. Each of the first five and the antiperiplanar $X = CH_2F$ compound have two nonequivalent H atoms in the methyl group. The gauche $X = CH_2F$ species have three nonequivalent H atoms. For $X = CF_nH_{(3-n)}$, we use the corresponding conformers of $X = CH_3$ as a comparison; for SiF_3, we use the corresponding conformers of SiH_3. We present the data in Figure 5 for the AIM method of analysis. This plot is described by the relationship $\{q_{Y=F}\{H_{Me}\} - q_{Y=H}\{H_{Me}\}\} = \{0.37 \pm 0.04\}\,\Delta\gamma + \{0.009 \pm 0.001\}$, $r = 0.944$, for AIM data. We find $\{q_{Y=F}\{H_{Me}\} - q_{Y=H}\{H_{Me}\}\} = \{0.27 \pm 0.03\}\,\Delta\gamma + \{0.002 \pm 0.001\}$, $r = 0.940$ for NPA data. These data establish that the potential-gradient model accounts for the charge variation in the CZ_3 groups as X is varied from EH_n to EF_n.

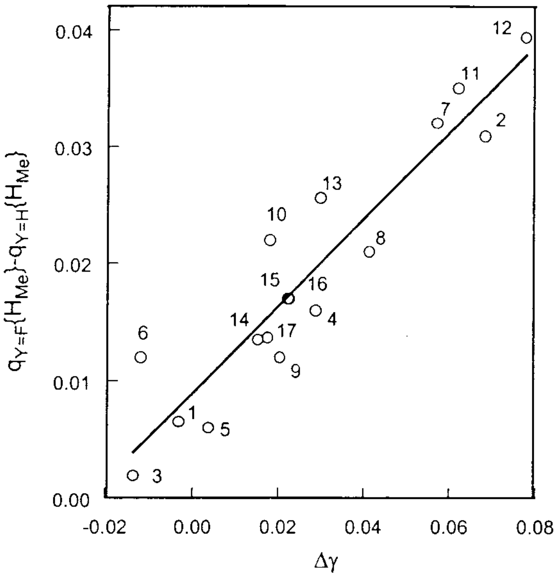

Figure 5. A plot of the difference in charge of the various hydrogen atoms in the methyl group upon the replacement of an $X = EF_nH_{3-n}$ group with an $X = EH_3$ group versus the corresponding change in the potential gradient, γ. The data points are, with eclipsed conformers indicated by an "e", $X = CH_2F$ with fluorine atom gauche to CH_3-methylene carbon bond, 1 is ap, 2 and 3, g; with fluorine atom antiperiplanar to CH_3-methylene carbon bond, 4, ap, and 5, g; $X = CHF_2$, 6, ap, and 7, g; $X = CF_3$, 8, ap, and 9, g; $X = CHF_2$ with hydrogen atom eclipsed with the CH_3-methylene carbon bond, 10, ap, and 11, g; X = e-CF_3, 12, syn, and 13, g; $X = SiF_3$, 14, ap, and 15, g; X = e-SiF_3, 16, syn, and 17, g.

For charged X, we have two pairs of $EH_n{}^q/EF_n{}^q$ if we neglect the $X = CH_2{}^-/CF_2{}^-$ couple because the lone pairs play a disruptive role. These two pairs yield eight data points. These fall on a straight line (AIM data) governed by the equation $\{q_{Y=F}\{H_{Me}\} - q_{Y=H}\{H_{Me}\}\} = \{0.65 \pm 0.03\}\,\Delta\gamma + \{0.006 \pm 0.001\}$, $r = 0.994$. The NPA data show more scatter, $\{q_{Y=F}\{H_{Me}\} - q_{Y=H}\{H_{Me}\}\} = \{0.34 \pm 0.03\}\,\Delta\gamma + \{0.002 \pm 0.002\}$, $r = 0.955$, with all data points included. As we found in the last section, the slope of plots involving charged compounds are larger than those of neutral compounds.

5. Long-Range Effects in Charged Compounds. We have qualitatively rationalized the charges on the methyl hydrogen atoms of long chain compounds.[18] We now apply the potential-gradient model to the charge on the fluorine atoms of trifluoromethyl groups remote from a perturbing charge induced by the $NH_3{}^+$ group. We calculate γ, assuming it is generated by the charges of the atoms of the CH_2X group, for staggered and eclipsed $CF_3CH_2NH_3{}^+$ as well as for two antiperiplanar, longer chain compounds, $CF_3(CH_2)_nNH_3{}^+$, $n = 2, 4$, and for the twisted conformer with $n = 4$ resulting in a total of eleven different

TABLE 5: Value of Atomic Contributions to the Potential Gradient at Fluorine Atoms in Substituted Ammonium Ions[a]

compound/F	r_{N-bcp}[b]	θ_N[c]	γ_N	γ_H[d]	γ_C	γ
$CF_3CH_2NH_3^+$						
F_{ap}	5.30	29.5	−0.2022	0.2286	0.0715	0.1148
F_g	4.69	80.6	−0.0426	0.0169	0.0711	0.0760
e-$CF_3CH_2NH_3^+$						
F_{syn}	4.58	94.9	−0.0227	−0.0640	0.0683	0.0631
F_g	5.20	49.4	−0.1527	0.1645	0.0691	0.1019
$CF_3(CH_2)_2NH_3^+$						
F_{ap}	7.80	43.6	−0.1118	0.1195	0.0525	0.0825
F_g	7.41	75.0	−0.0421	0.0488	0.0126	0.0200
$CF_3(CH_2)_4NH_3^+$						
F_{ap}	12.58	40.5	−0.0728	0.0839	0.0271	0.0505
F_g	12.11	79.1	−0.0188	0.0239	0.0043	0.0101
$CF_3(CH_2)_4NH_3^{+}$[e]						
F_a	11.18	17.5	−0.1028	0.1216	0.0332	0.0657
F_b	10.46	85.6	−0.0089	0.0114	0.0015	0.0036
F_c	10.06	115.3	0.0512	−0.0690	−0.0070	−0.0260

[a] The compounds have C_s symmetry unless otherwise noted. The total potential gradient is composed of a contribution from the methylene hydrogen atoms as well as those listed in the table. [b] The distance from the nitrogen atom to the bond critical point of the indicated carbon−fluorine bond in atomic units. [c] The angle the vector from the nitrogen atom to the bond critical point makes with the carbon-to-fluorine bond vector. [d] Sum of the contribution from the three hydrogen atoms attached to the nitrogen atom. [e] This molecule is twisted as indicated in the text.

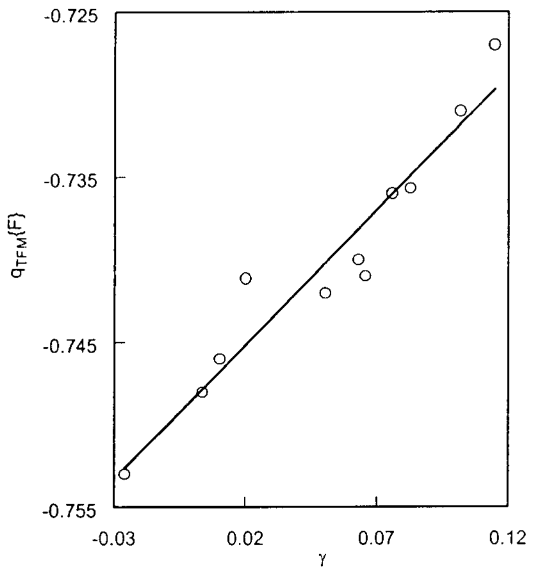

Figure 6. The correlation between the charge on fluorine atoms in various trifluoromethyl compounds containing an ammonium group and the calculated potential gradient at the C−F critical point. Reading from the left, the data points are F_c of the twisted conformer of $CF_3(CH_2)_4NH_3^+$, see Figure 2; F_b of the twisted butane; F_g of C_s conformer of $CF_3(CH_2)_4NH_3^+$; F_g of $CF_3(CH_2)_2NH_3^+$; F_{ap} of $CF_3(CH_2)_4NH_3^+$; F_{syn} of X = e-NH_3^+; F_a of twisted $CF_3(CH_2)_4NH_3^+$; F_g of X = NH_3^+; F_{ap} of $CF_3(CH_2)_2NH_3^+$; F_g of X = e-NH_3^+; F_{ap} of X = NH_3^+.

fluorine atom environments. In the last three compounds, both the distances and angles vary significantly. The data for these calculations with the AIM method are given in Table 5. In these data there is no attempt to compensate for the methylene carbon atoms. In Figure 6, we plot the charge on the remote fluorine atoms versus γ. The resulting straight line is given by $q_{TFM}\{F\} = (0.16 \pm 0.02)\ \gamma - (0.748 \pm 0.001)$, $r = 0.961$. The effect of distance can clearly be seen in the values for $CF_3(CH_2)_4NH_3^+$ where γ is small. In the twisted conformer of $CF_3(CH_2)_4NH_3^+$, there are three nonequivalent fluorine atoms which we label F_a, F_b, and F_c, see Figure 2. The C−F_c bond points more or less toward the ammonium group, in contrast to all other C−F bonds that we have studied. This gives rise to a reversal in the sign of γ. Indeed, the charge on this fluorine atom is −0.753, more negative than any fluorine atom in any ammonium derivative and even more negative than fluorine atoms in $CF_3CH_2CH_3$. Once again, this stresses the importance of θ in determining the charge on the peripheral atoms. Although the net values of γ are the result of the difference between large numbers, see Table 5, the reasonable correlation shown in Figure 6 testifies to the success of the model.

An analogous plot using charges derived from the NPA method is linear for the fluorine atoms in staggered and eclipsed $CF_3CH_2NH_3^+$. The points for the longer chain derivatives, however, fall off this line. Examination of the charges on the four kinds of atoms used to generate the potential-energy gradient, γ, indicates the cause of the deviation is the sign of the charge of the methylene carbon atom. Whereas the charges of the nitrogen atom, the three hydrogen atoms attached to it, and the hydrogen atoms at the methylene carbon center are *roughly* equivalent in the two methods of analysis, the methylene carbon atom charge differs significantly and in sign: 0.42 (AIM) and −0.30 (NPA). This does not affect the relative values of γ for the four kinds of fluorine atoms in staggered and eclipsed trifluoroethyl derivatives because the structures of these compounds require that the methylene carbon atom influences these atoms roughly equally. But this large charge difference between the two methods of charge analysis has a drastic effect on the field at the fluorine atoms in the long-chain compounds. Reed and Weinhold[55] have discussed the large negative charge on carbon atoms in alkanes in the NPA model. They argue that dipolar distributions caused by the hybridization used in the technique will alter properties generated by this charge, such as molecular dipoles.[56] Presumably, such effects will also influence the interactions that we are attempting to model.

A similar treatment can be applied to the methyl hydrogen atoms of $CH_3CH_2NH_3^+$, in both staggered and eclipsed conformations, and to all of the hydrogen atoms other than those on C_1 of hexylammonium ion and a twisted pentylammonium ion.[18] We again use all the atoms in the CH_2X group as the source of the perturbation and examine the correlation between the γ value and the charge on these atoms. The data (AIM analysis) for all the hydrogen atoms follows the relationship $q\{H_{Me/my}\} = \{0.92 \pm 0.09\}\ \gamma + \{-0.034 \pm 0.005\}$, $r = 0.923$. Three of the four points for the ethyl derivatives fall above this line. Removing the ethyl derivatives from the plot, we find $q\{H_{Me/my}\} = \{0.75 \pm 0.07\} + \{-0.033 \pm 0.003\}$, $r = 0.949$. This may be an example of the methylene carbon atom influencing atoms on the methyl group via factors other than simple electrostatic interactions.[19,57] The data without the ethyl derivatives are shown in Figure 7.

6. A General Potential-Gradient Model. Throughout our application of the potential-gradient model for charge on peripheral atoms of substituted ethanes and trifluoroethanes, we have been concerned about how to minimize the role of the methylene carbon atom on the electrons in the C−Z bonds. Although we expect considerably more scatter with direct inclusion of the methylene carbon atoms in the model, we believe it is an exercise worth pursuing. A plot of the charge on the hydrogen atoms of the methyl group versus the γ value calculated from the charge, distance, and angle of each atom of the CH_2X group for all the compounds that we have studied shows considerable scatter. If we restrict our consideration to neutral compounds of the type X = EY_n, in which E is a first-row element, there is a reasonable relationship between charge on the hydrogen atoms and the calculated γ value. Since X =

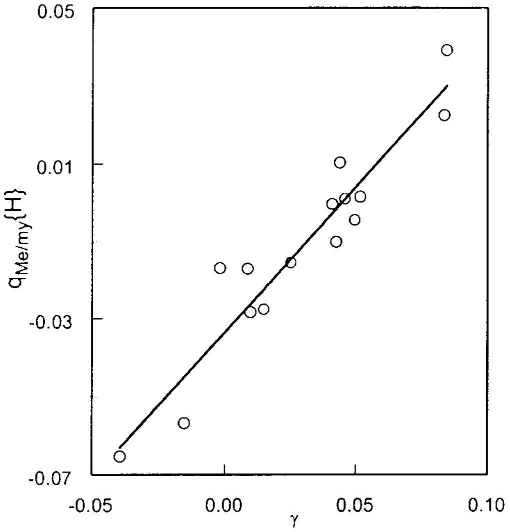

Figure 7. The correlation between the charge on hydrogen atoms in hexylammonium ion and a twisted pentylammonium ion versus the calculated potential gradient at the C−H bond. The two data points with negative γ are those in which the value of θ is greater than 90°, H5 and H7, see Figure 3 of ref 18.

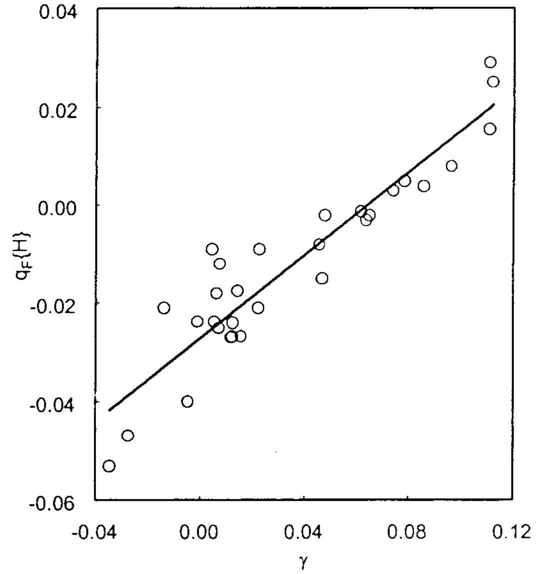

Figure 8. The charge on hydrogen atoms in neutral CH_3CH_2X (staggered and eclipsed), where $X = EY_n$ and E is a first-row element, versus the calculated potential gradient from all atoms of the CH_2X group. For identification of individual data points see Table S4 in the Supporting Information.

NH_2 and $X = NF_2$ make the plot considerably less linear for reasons mentioned above, we remove these points from consideration. The equation describing the data is $q_F\{H\} = \{0.43 \pm 0.03\} + \{-0.027 \pm 0.002\}\ \gamma$, $r = 0.933$, and the data are shown in Figure 8. Given that the points include compounds with X = F and X = OH, where the role of the methylene carbon atom is critically important, the agreement seems quite reasonable. The very high positive charges on the synperiplanar hydrogen atom of eclipsed X = F and eclipsed X = OH are caused by the positive methylene carbon atom. Neither the F nor the O or H of the OH group are effective because of θ values near 90°, despite their closeness to the synperiplanar hydrogen atom.

As discussed above, the compounds with $X = EY_n$ where E is a second-row element form a separate line. The number of data points is somewhat limited here, and the linear relationship is not so well established: $q_S\{H\} = \{0.27 \pm 0.04\} + \{-0.005 \pm 0.002\}\ \gamma$, $r = 0.900$. Nevertheless, some puzzling data are accommodated by this relationship: The gauche hydrogen atom with $X = SO_2F$ in the staggered configuration has a charge more positive than that of $X = NH_3^+$. This atom has a large positive γ that arises from a very positive sulfur atom. The sulfur atom also contributes positively to the γ of the antiperiplanar hydrogen atom, but the two oxygen atoms act very strongly on this hydrogen atom in a negative direction. These effects cancel each other for the antiperiplanar hydrogen atom but do not do so for the gauche ones.

The charged species also have a different functional relationship between the charge and the calculated value of γ. That relationship is $q_Q\{H\} = \{0.87 \pm 0.06\} + \{-0.020 \pm 0.005\}\ \gamma$, $r = 0.932$ for 30 entries with AIM charges, ($q_Q\{H\} = \{0.43 \pm 0.02\} + \{0.238 \pm 0.002\}\ \gamma$, $r = 0.970$, NPA) including the $X = CY_2^-$ compounds, $X = O^-$, and $X = PH_3^+$. For the last two entries, the points fall off the line in both methods of analysis. If these two compounds are removed, the relationships are $q_Q\{H\} = \{0.87 \pm 0.04\} + \{-0.018 \pm 0.003\}\ \gamma$, $r = 0.970$, AIM, and $q_Q\{H\} = \{0.42 \pm 0.01\} + \{0.238 \pm 0.001\}\ \gamma$, $r = 0.985$, NPA.

We observe different slopes for $X = EY_n^q$ when q is +1 or −1 compared to $q = 0$ and when E is a first-row element rather than a second-row element. The different slopes in the latter situation may be a function of the extra shell of electrons in the second-row elements. The portion of γ that originates on the X atoms has more electron density between it and the methyl hydrogen atoms as a result of the added shell. This extra electron density attenuates the potential gradient. In a simplistic fashion, those X which generate a positive γ should have, with attenuation, a smaller positive value than we calculate, and those X that produce a negative γ should have a smaller negative value. Accordingly, the slope of a charge versus γ plot is slightly lower than such a plot with first-row elements. For the charged compounds, all but one pair of which have first-row elements attached to the methylene carbon atom, the slope of charge versus γ is significantly larger than the neutrals. We suggest this may occur because the charge we are using to compute γ is the charge when electron density has reached its final state. Significantly more charge is shifted from the CH_2X group to the rest of the molecule for charged X than for neutral X. Before that charge is dissipated from the CH_2X group, the potential gradient is significantly higher. This leads to a greater charge on the peripheral atoms than the γ computed from the final-state electron density would suggest.

Conclusions. We present the computed charges by the AIM and NPA methods on the Z atoms in CZ_3CH_2X, (Z = F, H) in a large number of substituted alkanes in both the staggered and eclipsed conformations. The effect of X on the charge on Z is parallel for the two different Z atoms. We present and successfully test a semiquantitative electrostatic, through-space, potential-gradient model to account for the relative charges on the Z atoms induced by the charges on the atoms in the CH_2X fragment. Our model uses the bond critical point as the point of application of a potential-energy gradient. The agreement between the charge predicted by the potential gradient and that calculated by either the AIM or NPA method is satisfactory. We have applied the electrostatic model cautiously because it seems to us that point-charge electrostatic effects cannot dominate the interactions between atoms that are attached to each other, nor can the charge on the hydrogen (fluorine) atoms of the methyl (trifluoromethyl) group be dictated solely by the *final* charge of the atoms in the X group, as molecular charge is conserved. Nevertheless, the success that the model has in accounting for the difference in charge between an antiperiplanar and a gauche hydrogen atom, or the difference in charge of an atom close to a fluorine relative to one further away, is impressive. That the charges predicted by the potential gradient and those calculated by the quantum methods agree is strong support for a through-space mechanism of propagation. Our model naturally accounts for the difference between the previously observed[18] long-range charged X and the short-range uncharged X groups.

These results have implications in several areas. For example, they support the explanation for the observed stability of the axial conformer of 3-fluoropiperidinium ion[58] and the diaxial (fluorine) conformer of *cis*-3,5-difluoropiperidinium ion.[59] We have studied the two conformers of $CFH_2CH_2NH_3^+$, which serve as models for the axial and equatorial conformers of the former compound. We find at the HF/6-31+G*, B3LYP/6-311++G**, and MP2/6-311++G** (this last basis set successfully calculates the stability of the gauche conformer of 1,2-difluoroethane[60]) levels of theory that the gauche conformer is more stable than the antiperiplanar one by about 6 kcal mole^{-1}. A calculation using the charges typical of the atoms in $X = NH_3^+$ and $X = F$ groups gives a through-space electrostatic interaction that favors the gauche conformer by a similar amount. This arises because the interaction of the hydrogen atoms on the nitrogen atom, which are positively charged, with the negatively charged fluorine atom is of greater magnitude than the repulsive nitrogen atom−fluorine atom interaction. Another way to look at this phenomenon is to note our model predicts the antiperiplanar arrangement has a fluorine atom at a site where γ is large and positive, which generates a more positive charge on that fluorine atom than in the gauche environment. AIM calculations on $CH_2FCH_2NH_3^+$ support this; the charge on the fluorine atom in the gauche conformer is −0.734 charge units, whereas it is −0.720 for the antiperiplanar conformer. Second, there are several references to the energetic consequences of direct electrostatic interaction of substituents with reaction centers in the literature. Perhaps the most studied area is the stereoselectivity of nucleophilic addition to the carbonyl function.[61−67] At least one study has presented a quantitative relationship between semiempirical calculated dipoles and the selectivity.[66] Although the thrust of the work described here is concerned with small variations in the charge on atoms, the atomic charges we calculate are at least roughly transferable from molecule to molecule.[27] This suggests it may be possible to evaluate in a semiquantitative manner the changes in through-space electrostatic effects from those transferable atomic charges.

In summary, our analysis shows a through-space model rationalizes the atomic charges on the Z atoms of staggered and eclipsed CZ_3CH_2X as well as the charges on other atoms in these and other substituted alkanes. Forty years ago, Coulson wrote "... a charge cloud whose density varies from place to place cannot possibly be represented adequately by effective charges on the two nuclei."[68] Being in complete agreement with this statement, we are amazed by the remarkable predictive ability of our model.

Acknowledgment. We appreciate conversations with Professors Bickar, Kohen, Queeney, and Shea.

Supporting Information Available: Tables S1−S3, the NPA charges for staggered and eclipsed substituted trifluoroethanes and for eclipsed substituted ethanes, respectively. Numerical values of potential gradient for substituted ethanes (Table S4), trifluoroethanes (S5), and for fluorine atoms in alkylammonium ions (S6). This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Bachrach, S. M. *Population Analysis and Electron Densities from Quantum Mechanics*; Lipkowitz, K. B., Boyd, D. B., Eds.; VCH Publishers: New York, 1994; Vol. 5, pp 171−227.

(2) de Oliveira, A. E.; Haiduke, R. L.; Bruns, R. E. *J. Phys. Chem. A* **2000**, *104*, 5320−5327.

(3) Rousseau, B.; Peeters, A.; Van Alsenoy, C. *J. Mol. Struct. (THEOCHEM)* **2001**, *538*, 235−238.

(4) Williams, D. E. *J. Comput. Chem.* **1994**, *15*, 719−732.

(5) Wiberg, K. B.; Rablen, P. R. *J. Comput. Chem.* **1993**, *14*, 1504−1518.

(6) Hirshfeld, F. L. *Theor. Chim. Acta* **1977**, *44*, 129−138.

(7) Gill, P. M. W. *J. Phys. Chem.* **1996**, *100*, 15421−15427.

(8) Mulliken, R. S. *J. Chem. Phys.* **1955**, *23*, 1833−1841.

(9) March, J. *Advanced Organic Chemistry*, 3rd ed.; John Wiley & Sons: New York, 1985.

(10) Timoshbin, A. Y.; Suvorov, A. V.; Bettinger, H. F.; Schaefer, H. F., III *J. Am. Chem. Soc.* **1999**, *121*, 5687−5699.

(11) Taft, R. W.; Topsom, R. D. *Prog. Phys. Org. Chem.* **1987**, *16*, 1−83.

(12) Bowden, K.; Grubbs, E. J. *Chem. Soc. Rev.* **1996**, 171−177.

(13) Charton, M. *J. Phys. Org. Chem.* **1999**, *12*, 275−282.

(14) Exner, O. *J. Phys. Org. Chem.* **1999**, *12*, 265−274.

(15) Exner, O.; Charton, M.; Galkin, V. *J. Phys. Org. Chem.* **1999**, *12*, 289.

(16) Adcock, W.; Trout, N. A. *Chem. Rev.* **1999**, *99*, 1415−1435.

(17) Kaselj, M.; Chung, W.-S.; le Noble, W. J. *Chem. Rev.* **1999**, *99*, 1387−1413.

(18) Nolan, E. M.; Linck, R. G. *J. Am. Chem. Soc.* **2000**, *122*, 11497−11506.

(19) Nolan, E. M.; Linck, R. G. *J. Phys. Chem. A* **2001**, *105*, 7297−7307.

(20) Murcko, M. A.; Castejon, H.; Wiberg, K. B. *J. Phys. Chem.* **1996**, *100*, 16162−16168.

(21) Pophristic, V.; Goodman, L.; Guchhait, N. *J. Phys. Chem. A* **1997**, *101*, 4290−4297.

(22) Parra, R. D.; Zeng, X. C. *J. Fluorine Chem.* **1997**, *83*, 51−60.

(23) Parra, R. D.; Zeng, X. C. *J. Phys. Chem. A* **1998**, *102*, 654−658.

(24) Martell, J. M.; Boyd, R. J.; Shi, Z. *J. Phys. Chem.* **1993**, *97*, 7208−7215.

(25) Papasavva, S.; Illinger, K. H.; Kenny, J. E. *J. Phys. Chem.* **1996**, *100*, 10100−10110.

(26) Bader, R. W. F. *Acc. Chem. Res.* **1985**, *18*, 9−15.

(27) Bader, R. F. W. *Atoms in Molecules. A Quantum Theory*; Clarendon Press: Oxford, U.K., 1990.

(28) Weinhold, F. *Natural Bond Orbitals*; Schleyer, P. V. R., Ed.; John Wiley & Sons: New York, 1998; Vol. 3, pp 1792−1811.

(29) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Cioslowski, J.; Stefanov, B. B.; Nanayakkara, A.; Challacombe, M.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. *Gaussian 94*, revision B.2; Gaussian, Inc.: Pittsburgh, PA, 1995.

(30) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.6; Gaussian, Inc.: Pittsburgh, PA, 1998.

(31) Foster, J. P.; Weinhold, F. *J. Am. Chem. Soc.* **1980**, *102*, 7211−7218.

(32) Reed, A. E.; Weinhold, F. *J. Chem. Phys.* **1985**, *83*, 1736−1740.

(33) Reed, A. E.; Curtiss, L. A.; Weinhold, F. *Chem. Rev.* **1988**, *88*, 899−926.

(34) Biegler-Konig, F. W.; Bader, R. F. W.; Tang, T. H. *J. Comput. Chem.* **1982**, *3*, 317−328.

(35) Downloaded from http://www.chemistry.mcmaster.ca/aimpac, November, 1997.

(36) We use the symbol q to refer to charge. The subscript on this symbol refers to the environment of the atom or the class to which the atom belongs.

The brackets following the *q* indicate the identity of the atom, and a subscript on that symbol indicates the particular atom. Some abbreviations are: Me, methyl group; TFM, trifluoromethyl group; F, an X = EY_n with E a first-row element; S, an X = EY_n with E a second-row element; Q, a charged X group. Others are ap, antiperiplanar; g, gauche; syn, synperiplanar; xp, either antiperiplanar or synperiplanar; Me, methyl hydrogen; my, methylene. The symbol *r* is the correlation coefficient.

(37) See, for instance: Wiberg, K. B.; Laidig, K. E. *J. Org. Chem.* **1992**, *57*, 5092−5101.

(38) See also: Wiberg, K. B.; Clifford, S.; Jorgensen, W. L.; Frisch, M. J. *J. Phys. Chem. A* **2000**, *104*, 7625−7628.

(39) We define the carbon to which X is attached as C_1. In cases where the X group contains a carbon atom attached to the methylene group, this is inconsistent with standard nomenclature but leads to an internal consistency within our analysis.

(40) Kirkwood, J. G. *J. Chem. Phys.* **1934**, *2*, 351−361.

(41) Kirkwood, J. G.; Westheimer, F. H. *J. Chem. Phys.* **1938**, *6*, 506−512.

(42) Westheimer, F. H.; Kirkwood, J. G. *J. Chem. Phys.* **1938**, *6*, 513−517.

(43) Topsom, R. D. *Tetrahedron Lett.* **1980**, *1980*, 403−406.

(44) Topsom, R. D. *J. Am. Chem. Soc.* **1981**, *103*, 39−44.

(45) Yoder, C. S.; Yoder, C. H. *J. Am. Chem. Soc.* **1980**, *102*, 1245−1247.

(46) Hehre, W. J.; Taagepera, M.; Taft, R. W.; Topsom, R. D. *J. Am. Chem. Soc.* **1981**, *103*, 1344−1349.

(47) Benson, S. W.; Luria, M. *J. Am. Chem. Soc.* **1975**, *97*, 704−709.

(48) Luarencelle, N.; Pacey, P. D. *J. Am. Chem. Soc.* **1993**, *115*, 625−631.

(49) This approximation is surely wrong in detail. Building up charge on one atom in the molecule comes at the expense of another, so the charge we should use to determine whether electron density will move to or from Z is the charge on the atoms A before the electron density moves. We believe this situation is pertinent in our interpretation of our results. See Section 6.

(50) That the AIM and the NPA method agree in this analysis seems strange, given the lack of correlation between the charges on the methylene hydrogen atoms in the two methods. The source of the agreement is a correlation between the charges over the set of X groups chosen for this comparison.

(51) Thalladi, V. R.; Weiss, H.-C.; Blaser, D.; Boese, R.; Nangia, A.; Desiraju, G. R. *J. Am. Chem. Soc.* **1998**, *120*, 8702−8710.

(52) See also: Gibb, C. L. D.; Stevens, E. D.; Gibb, B. C. *J. Am. Chem. Soc.* **2001**, *123*, 5849−5850.

(53) Burkert, U.; Allinger, N. L. *Molecular Mechanics*; American Chemical Society: Washington, DC, 1982.

(54) Perrin, C. L.; Armstrong, K. B.; Fabian, M. A. *J. Am. Chem. Soc.* **1994**, *116*, 715−722.

(55) Reed, A. E.; Weinhold, F. *J. Chem. Phys.* **1986**, *84*, 2428−2430.

(56) See also: Monaco, G. *Int. J. Quantum Chem.* **1998**, *68*, 201−210.

(57) Nolan, E. M.; Linck, R. G., *to be submitted.*

(58) Lankin, D. C.; Chandrakumar, N. S.; Rao, S. N.; Spangler, D. P.; Snyder, J. P. *J. Am. Chem. Soc.* **1993**, *115*, 3356−3357.

(59) Snyder, J. P.; Chandrakumar, N. S.; Sato, H.; Lankin, D. C. *J. Am. Chem. Soc.* **2000**, *122*, 544−545.

(60) Wiberg, K. B.; Murcko, M. A.; Laidig, K. E.; MacDougall, P. J. *J. Phys. Chem.* **1990**, *94*, 6956−6959.

(61) Wong, S. S.; Paddon-Row, M. N. *J. Chem. Soc., Chem. Commun.* **1991**, *1991*, 327−330.

(62) Wong, S. S.; Paddon-Row, M. N. *Aust. J. Chem.* **1991**, *44*, 765−770.

(63) Wu, Y.-D.; Tacker, J. A.; Houk, K. N. *J. Am. Chem. Soc.* **1991**, *113*, 5018−5027.

(64) Paddon-Row, M. N.; Wu., Y.-D.; Houk, K. N. *J. Am. Chem. Soc.* **1992**, *114*, 10638−10639.

(65) Wu, Y.; Houk, K. N. *J. Am. Chem. Soc.* **1993**, *115*, 10992−10993.

(66) Wipf, P.; Jung, J.-K. *Chem. Rev.* **1999**, *99*, 1469−1480.

(67) Rosenberg, R. E.; Abel, R. L.; Drake, M. D.; Fox, D. J.; Ignatz, A. K.; Kwiat, D. M.; Schaal, K. M.; Virkler, P. R. *J. Org. Chem.* **2001**, *66*, 1694−1700.

(68) Coulson, C. A. *Valence*; Oxford University Press: New York and London, 1961.