Gas-phase Acidity of Polyfluorinated Hydrocarbons. Effects of Fluorine and the Perfluoroalkyl Group on Acidity

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Abstract

Gas-phase acidities of polyfluorinated hydrocarbons have been determined by measuring proton-transfer equilibria and by computing the free energies of deprotonated carbanions and the corresponding neutrals. An excellent linear relationship between acidities and the accumulated inductive effects of fluorine atoms contained in a molecule was observed for the perfluoroalkyl-substituted neopentanes, $(R_f^1)(R_f^2)(R_f^3)CCH_3$, and polyfluorinated bridgehead carbon acids where the contribution of negative hyperconjugation of the C_β -F bond to the stability of the conjugate anions is absent or negligibly small. On the basis of this relationship, the extent of β -fluorine negative hyperconjugation involved in acidities of polyfluorinated hydrocarbons could be evaluated quantitatively. The negative hyperconjugation was found to be negligibly small in the stable tertiary polyfluorinated carbanions while in the less stable primary and secondary carbanions the contribution of this effect is present certainly, indicating that the negative fluorine hyperconjugation is complementary to the stabilization by the accumulated inductive effect of fluorine atoms. The extent of negative hyperconjugation was found to increase in order of $CF_3CH_2^- < C_2F_5CH_2^- \approx C_3F_7CH_2^- < i-C_3F_7CH_2^-$, being qualitatively consistent with the elongation of the C_β -F bond by deprotonation.

The effect of α -fluorine on acidity was found to change complicatedly with the carbanion, *e.g.*, the α -fluorine substitution in CF_3CH_3 strengthens acidity, no effect in $(CF_3)_2CH_2$, and strengthens again acidity in $(i-C_3F_7)_2CH_2$. Such varying effect of α -fluorine in the polyfluorinated hydrocarbons would be caused by a subtle balance of effective electronegativity of an anionic center carbon, a varying p-p lone pair repulsion depending on the net negative charge at the formal charge center carbon, and the change in ability of β -F negative hyperconjugation caused by α -F substitution.

Introduction

Polyfluorinated compounds have received continuous attention in a wide field of fundamental and applied sciences such as synthetic chemistry^{1,2} and material science^{3,4} over a half century. Introduction of fluorine in hydrocarbons can impart interesting changes in physical and chemical properties.⁵⁻⁹ These changes are caused by the complicated interplay of different properties of fluorine (*i.e.*, electronegativity, inductive/field, resonance, hyperconjugation, p- π or p-p repulsion).¹⁰ α -Fluorine to a carbanion site is known to destabilize the site over that of hydrogen itself, and this effect was considered to result from a p-p lone pair repulsion between the anionic center and fluorine atom.¹¹⁻¹³ On the contrary, β -fluorine to a carbanion site can stabilize the negative charge. Polyfluorination or introduction of fluorinated substituents is now an established approach to design very acidic molecules.¹⁴⁻¹⁸ In particular, the acidifying effect of β -fluorine termed “fluorine negative hyperconjugation” has been studied extensively.¹⁹⁻²⁸ This concept was introduced in 1950 to explain the strong electron-withdrawing ability of the trifluoromethyl group.¹⁹ Theoretical studies revealed that the increase in acidity of fluorinated hydrocarbons is mainly due to the stabilization of the carbanion lone pair by the ability of the C $_{\beta}$ -F bond to delocalize the electron density of the carbanion lone pair to its energetically low-lying antibonding σ^* -orbital.²⁹⁻³³ An important piece of experimental evidence for this hypothesis was provided by Koppel and co-workers.¹⁵ They found that 1H,4H-dodecafluorobicyclo[2.2.1]heptane and 1H-undecafluorobicyclo[2.2.1]heptane in the gas phase are weaker acids than (CF₃)₃CH. This fact was attributed to no negative hyperconjugation of β -F in the bicyclo[2.2.1]heptane skeleton because the lone pair orbital of the conjugate anions of bridgehead carbon acids cannot interact with the antibonding σ^* orbital of a C $_{\beta}$ -F bond while there is no such restriction in the conjugate anion of (CF₃)₃CH. This conclusion was based on the assumption that the contribution

of inductive/field effect of the polyfluoroalkyl group is identical in the stability of both conjugate anions. However, there is no evidence for this assumption. Thus, most controversies about mechanisms for carbanion stabilization by fluorine or the polyfluorinated alkyl group are still qualitative. Therefore, it is important to understand quantitatively the effects of fluorine on the stability of a carbanion in order to design polyfluorinated hydrocarbons that are the most appropriate for a particular purpose. In this study, we determined experimentally and computationally gas-phase acidities which cover a wide variety of polyfluorinated hydrocarbons in structure, *i.e.*, acyclic and cyclic hydrocarbons, unsaturated hydrocarbons, and the effects of fluorine atoms and polyfluorinated alkyl groups on acidity were analyzed with the aid of theoretical calculations.

Results

Gas-phase acidity. The gas-phase acidity (GA) values of polyfluorinated carbon acids were determined from Gibbs' free energy changes for the proton-transfer equilibrium between a carbon acid (AH) of interest and an appropriate reference conjugate anion (A_o^-) of which acidity is known.

In Table 1 are summarized the GA values of a variety of polyfluorinated hydrocarbons determined in this study along with some related compounds available in the literature. For several fluorinated carbon acids having more than one acidic hydrogen atom, the deprotonation site was assigned on the basis of theoretical calculations (Table S1). The most acidic hydrogen is notated in italic in Table 1. In $CH_2=CFCH_3$ (**10**) and $CH_2=C(CF_3)CH_3$ (**11**) a hydrogen atom of the methyl group was more acidic than that connected to an sp^2 carbon. This is attributed to formation of a stable allylic carbanion in which negative charge is highly delocalized. On the contrary, in (*E*)- $CF_3CH=CHF$ (**12**), (*Z*)- $CF_3CH=CHF$ (**13**), (*E*)- $CF_3CH=CHCl$ (**14**), and $CF_3CH=CH_2$ (**34**) the

hydrogen atom adjacent to the trifluoromethyl group is more acidic than the terminal hydrogen. This would result from the high ability of the trifluoromethyl group to stabilize the carbanion. Table 1 shows that introduction of fluorine atom or polyfluorinated alkyl group within hydrocarbons dramatically increases its acidity, *i.e.*, ca. 100 kcal mol⁻¹ from ethane (GA = 411.7 kcal mol⁻¹³⁴) to (*i*-C₃F₇)₂(C₂F₅)CH (**4**, GA = 313.4 kcal mol⁻¹). The acidity of **4** is even stronger than trifluoroacetic acid, (GA = 317.4 kcal mol⁻¹³⁴) which is one of the strongest conventional organic acids.

[Tables 1 and 2]

Theoretical calculations. Neutral and deprotonated polyfluorinated hydrocarbons were optimized at the B3LYP/6-311+G(d,p) and MP2/6-311+G(d,p) levels of theory. Gas phase acidities were obtained from the Gibbs' free energy changes for reaction (2).

These results are listed in Table 1 (also Tables S1 and S2). Both levels of theory reproduced the experimental acidity values with satisfied precision. Closer inspection of the calculated acidities reveals that the acidity values of acyclic and cyclic polyfluorinated alkanes calculated at the B3LYP tend to be several kcal mol⁻¹ smaller than the experimental values while those of the propene derivatives show good agreement. The acidity values calculated at the MP2 for the former two alkane families are in good agreement with the experimental values while those for the propene derivatives are slightly worse than those at the B3LYP. Linear relationships between calculated and experimental acidities covering all compounds except difluoromethane (**21**) were obtained as follows,

$$\text{B3LYP} \quad \text{GA}_{\text{calc}} = 1.06\text{GA}_{\text{obs}} - 24.9 \quad (\text{R} = 0.991, \text{ n} = 22) \quad (3)$$

$$\text{MP2} \quad \text{GA}_{\text{calc}} = 1.02\text{GA}_{\text{obs}} - 7.8 \quad (\text{R} = 0.994, \text{ n} = 22) \quad (4)$$

These correlations indicate that the MP2 calculations seem to provide more accurate results than the B3LYP for describing acidities of polyfluorinated hydrocarbons. Therefore, the calculations at this level of theory were conducted for some fluorinated

alkanes for which experimental values are unavailable at the present stage. The results are given in Table 2.

There are also some differences in geometry between the two methods, *e.g.*, in the conjugate anion of **1** (**1a**, **a** notates anion) the calculated bond lengths of C_β-F *anti-periplanar* to the carbanion lone pair are 1.473 Å and 1.545 Å at the MP2 and B3LYP, respectively, while the corresponding values of the remaining two C_β-F bonds are close to each other, 1.381 Å and 1.385 Å. The bond lengths of C_α-C_β bonds are also different between the two methods, 1.418 Å and 1.398 Å at the MP2 and B3LYP, respectively. Similar differences were observed for other fluorinated hydrocarbons (Tables S3 and S4). Since there is no experimental information on the geometries of these carbanions, we cannot judge which method provides a more realistic structure. The success of theoretical methods in describing the energetics of the deprotonation process must depend on their ability to describe properly structural properties of the neutral acid and the carbanion formed after deprotonation. Since the agreement between experimental and theoretical acidity values is better in the MP2 method as noted above, we adopt geometries optimized at the MP2 throughout this paper. Some selected bond lengths are given in Fig. 1.

Discussion

Effects of perfluoroalkyl group on the gas-phase acidity. It was found that CF₃CH₃ (**1**) is 33.8 kcal mol⁻¹ more acidic than methane (GA = 409.9 kcal mol⁻¹ ³⁴) and (CF₃)₂CH₂ (**2**) is 27.4 kcal mol⁻¹ stronger than **1**. Furthermore, (CF₃)₃CH (**3**) is 22.1 kcal mol⁻¹ stronger acid than **2**. The effect of replacement of hydrogen in methane by the trifluoromethyl group is not constant and the effect of second and third substitution by the CF₃ group on the acidity is reduced compared to the first substitution. Such nonadditive effects of the second and third substitution on the gas-phase acidity were generally observed for multi-substituted methane derivatives, X_nCH_{4-n} (n = 1 – 3).³⁴ Acid-strengthening effect of substituent depends on its ability to stabilize negative

charge at the deprotonated site. In carbanions possessing a fluorine atom at the β -position of the anion center, the interaction of the formal center of negative charge with the neighboring C_β -F bonds was considered to stabilize negative charge, the so-called negative hyperconjugation.¹⁹⁻²⁸ In terms of molecular orbital theory, the effect was attributed to orbital interactions of the formal lone pair at the carbanionic center with the $\sigma^*(C_\beta-F)$ orbitals of proper orientation.²⁹⁻³³ According to this concept, the maximum contribution of the stabilizing effect exists when the C_β -F bond is oriented *anti-periplanar* to the formal lone pair at the anionic carbon. The C_β -F bond should be elongated as compared to the other C_β -F bonds with different orientation, and the C_α - C_β bond adjacent to the anionic center carbon should be shortened, resulting in an increase of planarity at the anionic center. Indeed, closer examination of the optimized structures of carbanions **1a**, **2a**, and **3a** shows that this effect seems to be present in these systems (Figure 1). In the structure of **1a** a single C_β -F bond is oriented *anti-periplanar* to the formal carbanion lone pair, leading to a large elongation of this C_β -F bond (1.473 Å) as compared to the other two C_β -F bonds in the CF_3 group (1.381 Å). The formal anionic center is somewhat pyramidal, *i.e.*, a sum of angles around the anionic center carbon is 339°.

Figure 1. Structures of representative carbanions and selected bond distances (in Å) optimized at the MP2/6-311+G(d,p) level of theory, for **4a** at the MP2/def2-TZVPP level. The values in parentheses denote the changes in bond distance by deprotonation (positive denotes elongation and negative denotes shortening).

For carbanion **2a** two stable conformers of which difference in stability is only 0.2 kcal mol⁻¹ were observed. In more stable conformer **2a-1**, the longest C_β-F bond of each trifluoromethyl group is in parallel with that of the other one and in the same direction. The anionic center is slightly pyramidal (sum of angles around the anion center carbon = 346.1°). The C_β-F bond is elongated by 0.078 Å compared with the neutral molecules. In the other conformer **2a-2**, the longest C_β-F bonds of two trifluoromethyl group are also in parallel with each other but in the opposite direction. In this conformation, when one of the C_β-F bonds stabilizes the negative charge through the fluorine negative hyperconjugation, the other C_β-F bond has no hyperconjugative interaction with the negative charge. However, the anionic center is planar and the elongation of 0.070 Å by deprotonation as well as the bond length is identical for both C_β-F bonds. This may be

due to the C2 symmetry in **2a-2**. The degree of elongation of the C_β-F bond in both conformers is smaller than that in **1** (elongation of 0.126 Å), suggesting that the negative hyperconjugation of the C_β-F bond is not so effective in **2a-1** and **2a-2**. This may result from the presence of two trifluoromethyl groups which can stabilize the negative charge by their inductive effects. Carbanion **3a** contains a fully planar carbanionic center. One of the three C_β-F bonds of each trifluoromethyl group is orthogonal to a lone pair orbital of the anionic center, and the dihedral angles between the remaining of C_β-F bonds and a lone pair orbital are twisted by ca. 30°. This leads to a quite small increase in length of two C_β-F bonds (1.382 Å, elongation of 0.013 Å) of each trifluoromethyl group. Similarly, deprotonation of (*i*-C₃F₇)₂(C₂F₅)CH (**4**) caused small changes in bond length similar to those of **3a**. In **4a** the C_β-F bond of the *i*-C₃F₇ moiety is orthogonal to the lone pair orbital, and one of two C_β-F bonds of the C₂F₅ moiety is twisted by ca. 50° from the lone pair orbital and the remaining C_β-F is orthogonal. These geometries and a faint elongation of the C_β-F bond by deprotonation suggest that the negative hyperconjugation is less important to determine the strong acidity of **4**.

Figure 1 shows that the extent of shortening of the C_α-C_β bond by deprotonation is nearly constant regardless of the different degree of negative hyperconjugation. The C_α-C_β bond length would be influenced not only by negative hyperconjugation but also by the release of steric strain in the tertiary carbon center by deprotonation. The latter factor may be the reason for the shortening in **3a** and **4a**. Accordingly, the extent of elongation of C_β-F bond by deprotonation may be a more suitable measure to describe the degree of β-fluorine negative hyperconjugation. Based on this criterion, the negative hyperconjugation decreases in order of **1a** > **2a** > **3a** ≥ **4a**. This leads us to the conclusion that in the less stable carbanion the contribution of β-fluorine negative hyperconjugation is more significant and *vice versa*. Indeed, recent theoretical calculations at the MP2/6-31+G(d) for a highly unstable artificial carbanion,

$\text{FCH}_2\text{CH}_2^-$, revealed that there was not a minimum on the potential energy surface and that complete transfer of negative charge to fluorine led to rupture of the C-F bond and formation of hydrogen bonded F^- ethylene complex during geometry optimization.³¹ We also optimized this anion at the MP2/6-311+G(d,p) level of theory. The carbanion (**a-1**) was found to be a local minimum, and the optimization of another conformer (**a-2**) led to ethylene associated with fluoride anion which is 40 kcal mol⁻¹ more stable than **a-1** (Scheme 1).

Scheme 1. Evolution of initial structures during optimization at the MP2/6-311+G(d,p) level of theory.

Formation of ethylene without any energy barrier is considered to result from an extremely strong interaction of a lone pair at the anion center with an antibonding σ^* orbital of a C-F bond. That is, a remarkable elongation of $\text{C}_\beta\text{-F}$ leads to cleavage of this bond and shortening a $\text{C}_\alpha\text{-C}_\beta$ bond leads to formation of a double bond. Similar results were obtained for the conjugate anion of difluoroethane, $\text{F}_2\text{CHCH}_2^-$. A conformer (**b-2**) in which fluorine atom is oriented *anti-periplanar* to the carbanion lone pair led to formation of the corresponding difluoroethylene associated with fluoride anion as a thermodynamically more stable species by ca. 10 kcal mol⁻¹ than **b-1** in which a

hydrogen of the F₂CH moiety is oriented *anti-periplanar* to the carbanion lone pair (Scheme 1). These theoretical calculations support strongly that the degree of fluorine negative hyperconjugation depends on instability of a carbanion and on the orientation of the C_β-F bond with respect to a carbanion lone pair orbital.

An important result in this study is that 1H-perfluoroadamantane (**7**) was 15 – 16 kcal mol⁻¹ more acidic than 1H,4H-dodecafluorobicyclo[2.2.1]heptane (**5**) and 1H-undecafluorobicyclo[2.2.1]heptane (**6**). The fact that the acidities of **5** and **6** are weaker than **3** was used as evidence for the presence of the negative hyperconjugation of C_β-F bond in **3a**.¹⁵ However, the bridgehead hydrogen acidity of 319.6 kcal mol⁻¹ observed for **7** is even stronger than that of **3**. The optimized structure of **7a** indicates that the C_β-F bonds as well as those in **5a** and **6a** cannot be oriented *anti-periplanar* to the carbanion lone pair. In addition, the elongation of the C_β-F bond and shortening of the C_α-C_β bond by deprotonation are also small similar to those in **5a** and **6a**. These facts suggest that the major cause of the high acidity of **7** is not β-fluorine negative hyperconjugation.⁴² The number of β-fluorine atoms is six in **7a** fewer than that in **3a** and instead there are three γ- and six δ-fluorine atoms in the former. In addition, (*i*-C₃F₇)₂(C₂F₅)CH (**4**) which contains four β- and fifteen γ-fluorine atoms was found to be the strongest polyfluorinated hydrocarbon acid reported so far. In **4a** orientation of C_β-F bonds suggest no stabilization of negative charge through fluorine negative hyperconjugation mechanism. These results indicate clearly that the acidity of polyfluorinated hydrocarbon is strongly influenced by inductive/field effects of fluorine atoms rather than β-fluorine negative hyperconjugation. The degree of elongation of the C_β-F bond and shortening of the C_α-C_β bond in **3a** are similar to those for **4a**, **5a**, **6a**, and **7a**, suggesting that the fluorine negative hyperconjugation in **3a** is also negligibly small even though it is present. On the other hand, in C₂F₅CH₂⁻ (**25a**), C₃F₇CH₂⁻ (**26a**), and *i*-C₃F₇CH₂⁻ (**27a**) the C_β-F bonds oriented *anti-periplanar* to a lone pair orbital are remarkably elongated by 0.453 Å, 0.513 Å, and 0.619 Å, respectively, by deprotonation.

This suggests that when the C_β atom connects with a strong electron-withdrawing group the ability of negative hyperconjugation of the C_β-F bond is enhanced. This may be due to a lower lying σ* orbital of the C_β-F bond. Acidities of these three carbon acids stronger than **1** by 8.7, 11.9, and 23.4 kcal mol⁻¹ for **25**, **26**, and **27**, respectively, would result from the enhanced hyperconjugation.

It should be noted that *cis-cyclo*-C₄H₂F₆ (**9**) is a stronger acid by 1.5 kcal mol⁻¹ than *trans-cyclo*-C₄H₂F₆ (**8**). This difference in acidity between **8** and **9** arises from the difference in stability between the corresponding neutrals because both neutrals form an identical carbanion by deprotonation. In this conjugate carbanion, a C_β-F bond at the C2 position is elongated significantly to 1.502 Å and two C_β-F bonds at C4 are also elongated to 1.425 Å and 1.416 Å. The C1C2 and C1C4 bonds are shortened and the cyclobutane ring is almost planar while their neutrals have a twisted conformation. These geometric features suggest that the formal negative charge at C1 in the conjugate anion is delocalized over these three carbons. Table 1 shows another interesting result that **13** is 1.1 kcal mol⁻¹ more acidic than **12**. In **12a** the C-F bond of the CF₃ group is oriented *anti-periplanar* to a lone pair orbital while in **13a** the terminal C-F bond of the vinyl group is oriented *anti-periplanar* to a lone pair orbital, and the degree of elongation of the C-F bond is larger in **13a** than that in **12a**, 1.435 Å (elongation of 0.103 Å) in **13a** and 1.409 Å (elongation of 0.064 Å) in **12a** although there are two C_β-F bonds oriented *anti-periplanar* to a lone pair orbital in **12a**. These differences in geometry suggest that the negative hyperconjugation of the vinyl C_β-F bond in **13a** is more effective than that of the CF₃ group in **12a**.

Relationship between gas-phase acidity and the number of fluorine atoms. As seen above, fluorine atoms other than β-F also play an important role to determine acidity of polyfluorinated hydrocarbons, indicating a significant contribution of field/inductive effect of fluorine atoms. To analyze quantitatively factors governing the acidity of

polyfluorinated hydrocarbons it is necessary to separate the apparent acidifying effect of the polyfluoroalkyl group into two factors at least, field/inductive effect and negative hyperconjugation effect. As the first analysis, we tried to estimate the contribution of the inductive effect of fluorine on the acidity of polyfluorinated hydrocarbons. For this purpose, we focused on two series of which acidities are determined only by inductive effect of fluorine atoms. One is the perfluoroalkyl-substituted neopentane family, **35** – **38**, $(R_f^1)(R_f^2)(R_f^3)CCH_3$ where R_f is the perfluoroalkyl group. In particular, this series would play a key role to estimate the contribution of field/inductive effect of fluorine atoms because there is no β -fluorine atom in these fluoroalkanes and because a relatively wide range of acidity can be covered by variation of the R_f group. The other is the bridgehead hydrogen acids, **5**, **6**, **7**, and **33**, with negligibly small negative hyperconjugation as discussed above. Although the experimental acidity values for $(R_f^1)(R_f^2)(R_f^3)CCH_3$ are unavailable in the literature, we used the calculated values at the MP2 level of theory because of an excellent agreement with experimental values for polyfluorinated alkanes as seen above. The acidities of these compounds increase with the size and number of the R_f group. Its increase would depend on the polar effect of the R_f moiety which results from the accumulated inductive effect of fluorine atoms contained in the R_f moiety, but also from the increase of polarizability of the R_f group with its size. This may lead to the possibility of an empirical approach for prediction of gas-phase acidity. Since the inductive effects of fluorine atoms on the stability of the acid's conjugate anions should depend on the distance (or number of insulating carbon atoms) between a formal anionic center and fluorine⁴³⁻⁴⁷ and on the number of fluorine atoms contained in the polyfluorinated hydrocarbon, we propose that the acidities of two fluoroalkane families noted above may be described in terms of equation (4) as a simple approximation.

$$GA = \rho (N_{(\beta)} + a N_{(\gamma)} + b N_{(\delta)}) + d \quad (5)$$

where GA is the gas-phase acidity, $N_{(\beta)}$, $N_{(\gamma)}$, and $N_{(\delta)}$ are numbers of fluorine atoms at β ,

γ , and δ position of the formal negative charge center, respectively. We term the sum in the parentheses of eq 5 as the corrected number of fluorine atoms in the R_f moiety. Because the increase of the inductive effect in this equation implicitly accounts also for the increase of R_f group polarizability with the increase of R_f size. An application of equation (5) to the bridgehead carbon acids and the neopentane series including ethane as an origin (no fluorine) gave equation (6) with excellent precision (correlation coefficient = 0.998, $n = 9$).

$$GA = -9.71(N_{(\beta)} + 0.41N_{(\gamma)} + 0.30N_{(\delta)}) + 410.6 \quad (6)$$

The coefficients of respective parameters indicate that the stabilization of negative charge by inductive/field effect of fluorine atoms decreases consistently with the number of inserted carbon atoms. The relative coefficient of 0.41 for γ -F is consistent with the attenuation factor by intervening a methylene group between a reaction center and the substituent observed in many cases.⁴³⁻⁴⁵ A factor of 0.30 for δ -F seems to be somewhat large. This may be attributed to the polarizability effect which is automatically included in eq 5 because polyfluorinated hydrocarbons having the δ -F atoms would have an important polarizability effect due to a large carbon skeleton.⁴⁸

Figure 2. Plot of gas-phase acidities against the corrected number of fluorine atoms,

solid line; $GA = -9.71N + 410.6$ ($R = 0.998$). Open squares denote bridgehead carbon acids, **5**, **6**, **7**, and **33**. Arrows indicate the acidifying effect of β -fluorine negative hyperconjugation.

Figure 2 shows plots of acidities of polyfluorinated hydrocarbons against the corrected number of fluorine atoms in a carbanion given by $N = 1.00N_{(\beta)} + 0.41N_{(\gamma)} + 0.30N_{(\delta)}$. On the basis of a straight line obtained for nine carbon acids (open circles and squares), the downward deviations are observed for several carbon acids (closed circles), indicating that acidities of these carbon acids are higher than the predicted ones based on the accumulated inductive effect of fluorine atoms. The enhanced acidities observed for **1**, **2**, and **25 - 30** would be due to an additional stabilization of the corresponding conjugate anions by β -fluorine negative hyperconjugation. The degree of the negative hyperconjugation effect involved in the respective acidities can be estimated from the magnitude of these deviations from the solid line in Fig. 2. The results are summarized in Table 3. The acidifying effect of $35.6 \text{ kcal mol}^{-1}$ caused by the CF_3 group in **1** can be divided into two contributions of $30.8 \text{ kcal mol}^{-1}$ by its inductive effect and $4.8 \text{ kcal mol}^{-1}$ by β -fluorine negative hyperconjugation. In **27** the acidifying effect by accumulated inductive effect of fluorine atoms is estimated to be $35.2 \text{ kcal mol}^{-1}$ and that by negative hyperconjugation is $23.8 \text{ kcal mol}^{-1}$. Thus, the accumulated inductive effect of fluorine atoms is more important to determine acidities of polyfluorinated hydrocarbons than negative hyperconjugation. Furthermore, the ability of the negative hyperconjugation of the $\text{C}_\beta\text{-F}$ bond was found to increase in order of $\text{CF}_3\text{CH}_2^- < \text{C}_2\text{F}_5\text{CH}_2^- \approx \text{C}_3\text{F}_7\text{CH}_2^- < i\text{-C}_3\text{F}_7\text{CH}_2^-$ and $(\text{CF}_3)_2\text{CH}^- < (\text{CF}_3)(\text{C}_2\text{F}_5)\text{CH}^- < (\text{C}_2\text{F}_5)_2\text{CH}^- < (i\text{-C}_3\text{F}_7)_2\text{CH}^-$. This is qualitatively consistent with the elongation of the $\text{C}_\beta\text{-F}$ bond (Table 3).

[Table 3]

It should be noted that **3**, **4**, **31**, and **32** (gray circles in Fig. 2) conform the

line within the allowable margin of correlation error ($2 - 3 \text{ kcal mol}^{-1}$), indicating that the fluorine negative hyperconjugation in these stable carbanions is negligibly small. This is completely consistent with their geometric features mentioned above, *i.e.*, feasible elongation of the C_β -F by deprotonation. It is concluded that the contribution of negative hyperconjugation is complementary to other stabilizing factors such as accumulated inductive effect of fluorine atoms contained in the R_f moiety.

Effects of α -fluorine on the acidity of carbon acids. Table 4 summarizes effects of α -fluorine substitution on acidity and geometric features. A successive replacement of hydrogen in methane by fluorine increases its acidity from $409.9 \text{ kcal mol}^{-1}$ for CH_4 *via* $400.6 \text{ kcal mol}^{-1}$ ($GA_{\text{calc}} = 403.3$) for CH_3F (**22**) and $391.3 \text{ kcal mol}^{-1}$ for CH_2F_2 (**21**) to $370.3 \text{ kcal mol}^{-1}$ for CHF_3 (**20**). Such an increase in acidity is explained by the electron-withdrawing effect of fluorine with high electronegativity. The increment of acidifying effect of the F-substitution is not constant; the first and second replacement acidify by $9.3 \text{ kcal mol}^{-1}$ (or $6.6 \text{ kcal mol}^{-1}$ for first and $12.0 \text{ kcal mol}^{-1}$ for the second replacement when the calculated GA for **22** is used) and $21.0 \text{ kcal mol}^{-1}$ for the third one. Similarly, an acidifying effect of $6.3 \text{ kcal mol}^{-1}$ for the second substitution larger than the first one ($3.0 \text{ kcal mol}^{-1}$) was observed for CF_3CH_3 . These results are not consistent with a general observation that a successive replacement by the electron-withdrawing group shows a smaller effect with the increasing number of substituent as seen in the effect of the CF_3 group. The unusual effect of α -fluorine substitution suggests that the electron-withdrawing effect of fluorine arising from its high electronegativity and the destabilizing effect caused by p-p lone pair repulsion between a lone pair orbital and p-orbital of fluorine vary with carbanion. In fact, the calculated C_α -F bond in **20a** is shorter than those in **21a** and **22a**. In addition, the extent of elongation ($0.057 \text{ \AA}$) of the C_α -F caused by deprotonation was found to be much smaller than those in **21a** ($0.107 \text{ \AA}$) and **22a** ($0.108 \text{ \AA}$), suggesting the reduced p-p lone

pair repulsion in **20a**. This may be due to the dispersion of the negative charge to three fluorine atoms. As a result of this, the electron-withdrawing effect of the third α -fluorine substitution becomes relatively more significant, resulting in the large increase of acidity for **20**.

[Table 4]

The effect of a single α -fluorine changes significantly from $-9.3 \text{ kcal mol}^{-1}$ for **22** to $2.5 \text{ kcal mol}^{-1}$ (decrease in acidity) for $(\text{C}_2\text{F}_5)_2\text{CHF}$ (**43**), and the change is quite complicated. Primary and secondary carbon acids behave in a different manner by α -fluorine substitution. In the primary carbon acids **22** and **39** the $\text{C}_\alpha\text{-F}$ bond is elongated by ca. $0.1 \text{ \AA}$ by deprotonation. The planarity at the anionic center of their conjugate anions decreases, resulting in a more pyramidal structure compared with that of α -H-substituted carbanions. Such changes in structure suggest the presence of a strong p-p repulsion. On the contrary, in $\text{C}_2\text{F}_5\text{CHF}^-$ (**40a**), $\text{C}_3\text{F}_7\text{CHF}^-$ (**41a**), and *i*- $\text{C}_3\text{F}_7\text{CHF}^-$ (**42a**) neither elongation of $\text{C}_\alpha\text{-F}$ bond by deprotonation nor change in planarity at the anionic center by α -fluorine substitution was observed. Instead, a longer $\text{C}_\beta\text{-F}$ bond and a shorter $\text{C}_\alpha\text{-C}_\beta$ bond than those for the parent α -H-substituted carbanion were observed, suggesting importance of the β -fluorine negative hyperconjugation in these three carbanions. Thus, there are apparent differences between the former two carbanions and latter three. α -Fluorine substitution would cause the abstraction of an electron at the formal anionic center to a fluorine atom, p-p repulsion, and a change in $\text{C}_\beta\text{-F}$ negative hyperconjugation. Effective electronegativity of the anion center carbon atom may become larger when an electron-withdrawing group is bonded to the carbon, and this would result in reduction of p-p repulsion. As mentioned above, when an electron-withdrawing group is bonded to the β -carbon, $\text{C}_\beta\text{-F}$ negative hyperconjugation is enhanced. This is also the case for α -fluorine substitution. That is, the α -fluorine substitution enhances the $\text{C}_\beta\text{-F}$ negative hyperconjugation. As a result of these changes, in **40a** - **42a** the fluorine negative hyperconjugation becomes more significant than that

in the corresponding α -H-substituted carbanions.

In the secondary polyfluorinated hydrocarbon acids, **17** and **43**, the elongation of C_α -F bonds and decrease of planarity at the anionic center by α -fluorine substitution were observed, indicating again importance of the p-p repulsive interaction. In addition, a shorter C_β -F bond and a longer C_α - C_β bond than those for the parent α -hydrogen-substituted carbanion were observed though these changes are small, indicating that α -fluorine substitution does not cause any change in the fluorine negative hyperconjugation. As a result of these factors, the effects of α -fluorine substitution in **17** and **43** result in a small acidifying and/or weakening of acidity. On the contrary, in $(i\text{-C}_3\text{F}_7)_2\text{CHF}$ (**44**) elongation of C_β -F bond and shortening of C_α - C_β bond by deprotonation were again observed while neither elongation of C_α -F bond nor change in planarity of the central carbon by α -fluorine substitution was observed, revealing clearly the predominance of the fluorine negative hyperconjugation in **44a**. This suggests further that the β -fluorine negative hyperconjugation is enhanced by α -fluorine substitution. This is consistent with the observation mentioned above that the ability of negative hyperconjugation of the C_β -F bond is enhanced when the C_β connects with a strong electron-withdrawing group.

In conclusion, the effects of α -fluorine on acidity of the polyfluorinated hydrocarbons are quite complicated depending on their molecular structures. Such varying effects of α -fluorine would be caused by a subtle balance of effective electronegativity of an anionic center carbon, a varying p-p lone pair repulsion depending on the net negative charge at the formal charge center carbon, and the change in β -F negative hyperconjugation caused by α -fluorine substitution. Further studies are clearly necessary to understand quantitatively effects of α -fluorine on the acidity.

Conclusion

An excellent linear relationship between acidities and accumulated inductive

effects of the fluorine atoms contained in the polyfluorinated alkanes was observed for the perfluoroalkyl-substituted neopentane system, $(R_f^1)(R_f^2)(R_f^3)CCH_3$, and bridgehead carbon acids where the contribution of negative hyperconjugation of the C_β -F bond is absent or negligibly small. This relationship could lead to quantitative estimation of β -F negative hyperconjugation involved in the acidity of polyfluorinated hydrocarbons. The negative hyperconjugation was found to be negligibly small in the stable tertiary polyfluorinated carbanion such as **3a**, **4a**, **31a**, and **32a** while in the less stable primary and secondary carbanions, $R_fCH_2^-$ and $(R_f)_2CH^-$, this effect is present certainly, indicating that the negative hyperconjugation is complementary to the stabilization by accumulated inductive effect of fluorine atoms. The extent of negative hyperconjugation was found to be also influenced by the substituent at the C_β carbon, *e.g.*, the effect increased in order of $CF_3CH_2^- < C_2F_5CH_2^- \approx C_3F_7CH_2^- < i-C_3F_7CH_2^-$, being consistent with the elongation of the C_β -F bond.

The effect of α -fluorine was found to change complicatedly with the carbanion, *e.g.*, the introduction of α -fluorine to CF_3CH_3 strengthens acidity, no effect in $(CF_3)_2CH_2$, and in $(i-C_3F_7)_2CH_2$ strengthens again acidity. Such varying effect of α -fluorine substitution in the polyfluorinated hydrocarbons would be caused by a subtle balance of effective electronegativity effect of an anionic center carbon, a varying p-p lone pair repulsion depending on the net negative charge at the formal charge center, and the change in β -F negative hyperconjugation caused by α -F substitution.

Experimental

Chemicals. All materials otherwise noted were used as purchased without further purification. *Preparation of 1-H-pentadecafluoroadamantane.*⁴⁹ To a solution of pentadecafluoroadamantane-1-carbonylfluoride (1.35 g, 2.99 mmole) in 5 mL of ether (not dried, thus, contained 39.3 mg of water) was added 50 mg (2.9 mmol) of water. The mixture was stirred for 12 h at room temperature. Evaporation of solvent in vacuo

afforded 1.2 g of a white solid (yield, 98.8%). This material was characterized as follows, ^1H NMR (300 MHz, CDCl_3): δ 3.91 (m, 1H); ^{19}F NMR (282.2 MHz, CDCl_3): δ -108.8 (bs, 6F), -120.4, -121.7 (AB q, 293.1 Hz, 6F), -219.5 (bs, 3F), MS: m/z 387 (M-F, 6.8), m/z 69 (CF_3^+ , base peak) and H-containing fragment ions, proof for the existence of H in the structure, m/z 201 (C_4HF_8^+ , 22.0), m/z 51 (CHF_2^+ , 4.1). These spectral data were in agreement with those for 1H-perfluoroadamantane in the literature.⁵⁰

Gas-phase acidity measurement. The gas phase acidity measurements were performed on an Extrel FTMS 2001 Fourier transform ICR spectrometer equipped with an IonSpec Data station. Most of the experimental techniques used for the measurements of the equilibrium constants of the proton-transfer reactions (eq. 10) are the same as the general procedures in the literature.^{51,52} Equations 7 - 9 describe the sequence of reactions which occur in a typical experiment, where AH and A_0H are the measured acid and the reference acid, respectively.

An experiment is initiated by a 5 ms pulse of a low-energy electron beam (0.3 to 0.5 eV) through the ICR cell. The electrons are captured by methyl nitrite at a partial pressure of $1 - 2 \times 10^{-7}$ torr and CH_3O^- is produced (eq. 7). The acids AH and A_0H react with CH_3O^- to yield M-1 negative ions (eqs. 8, 9). The partial pressures of the neutrals were maintained at lower than 4×10^{-7} torr. The equilibrium constant K for reaction (eq. 10) was evaluated from the expression $K = [\text{A}_0^-/\text{A}^-][\text{AH}/\text{A}_0\text{H}]$. The relative abundances of ions A^- and A_0^- were determined by the relative intensities of FT-ICR mass spectra signals when the equilibrium was attained. The time for the establishment of equilibrium was between 500 ms and 50 s, depending upon the pressure and molecular

structure of neutrals. Each measurement was performed at several ratios of partial pressures and at different overall pressures. The pressures of the neutral reactants were measured by means of a Bayard-Alpert ionization gauge with appropriate correction factors being applied to convert the gauge readings to relative intensities of the various compounds.^{53,54} Arithmetic mean values of K were used to calculate $\delta\Delta G^\circ (= -RT\ln K)$ with an average uncertainty of ± 0.2 kcal mol⁻¹ in most cases. Ion-eject experiments were also carried out to ensure that proton-transfer reactions occurred. The gas-phase acidity values for the reference compounds were taken from the literature.³⁵ All measurements were carried out at 303 - 313 K. The free energy of each proton transfer equilibrium and the selected acidity values are listed in Table 5.

[Table 5]

Calculations. DFT and MP2 calculations were carried out using the Gaussian 09 program.⁵⁵ The geometries were fully optimized at the B3LYP/6-311+G(d,p) and MP2/6-311+G(d,p) levels of theory. Vibrational normal mode analyses were performed at the same level to ensure that each optimized structure was a true minimum on the potential energy surface and to obtain thermodynamic quantities. The ORCA Ver. 2.9⁵⁶ was used for the calculations of **4** at the MP2/def2-TZVPP level of theory.

Supporting information: Details of the calculated energies and optimized geometries. This material is available free of charge on the Web at: www://csj.jp/journals/bcsj/.

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References

1. Acid Catalysis in Modern Organic Synthesis (Eds.: H. Yamamoto, K. Ishihara), Wiley-VCH, Weinheim, **2008**.
2. H. Yanai, H. Ogura, H. Fukaya, A. Kotani, F. Kusu, T. Taguchi, *Chem. Eur. J.* **2011**, *17*, 11747–11751.
3. K. Xu, *Chem. Rev.* **2004**, *104*, 4303–4417.
4. M. Armand, F. Endres, D. MacFarlane, H. Ohno, B. Scrosati, *Nature Materials* **2009**, *8*, 621–629.
5. J. H. Holloway, *J. Fluor. Chem.* **2000**, *104*, 3–4.
6. P. Kirsch, “Modern Fluoroorganic Chemistry. Synthesis, Reactivity, Applications.” **2004**, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.
7. T. Hiyama, “Organofluorine Compounds: Chemistry and Applications,” **2000**, Springer-Verlag, Berlin.
8. K. Uneyama, “Organofluorine Chemistry,” **2006**, Blackwell Publishing Ltd. Oxford, UK.
9. M. P. Krafft, J. G. Riess, *Chem. Rev.* **2009**, *109*, 1714–1792.
10. C. Hansch, A. Leo, R. W. Taft, *Chem. Rev.* **1991**, *91*, 165–195.
11. H. G. Adolph, M. J. Kamlet, *J. Am. Chem. Soc.* **1966**, *88*, 4761–4763.
12. M. Schlosser, *Angew. Chem. Int. Ed.* **1998**, *110*, 1496–1513.
13. F. Faigl, E. Marzi, M. Schlosser, *Chem. Eur. J.* **2000**, *6*, 771–777.
14. L. Lipping, I. Koppel, I. A. Koppel, A. Kolomeitsev, G.-V. Röschenthale, I. Leito, *J. Org. Chem.* **2010**, *75*, 6436–6400.
15. I. A. Koppel, V. Pihl, J. Koppel, F. Anvia, R. W. Taft, *J. Am. Chem. Soc.* **1994**, *116*, 8654–8657.
16. A. Guerrero, R. Herrero, J. Z. Dávalos, I. Koppel, J.-L. M. Abboud, I. A. Koppel, *J. Phys. Chem. A* **2009**, *113*, 6422–6429.
17. L. Lipping, I. Leito, I. Koppel, I. A. Koppel, *J. Phys. Chem. A* **2009**, *113*, 12972–12978.
18. I. A. Koppel, P. Burk, I. Koppel, I. Leito, T. Sonoda, M. Mishima, *J. Am. Chem.*

- Soc.* **2000**, *124*, 5114–5124.
19. J. D. Robert, R. L. Webb, E. A. McElhill, *J. Am. Chem. Soc.*, **1950**, *72*, 408–411.
 20. (a) D. Holtz, *Prog. Phys. Org. Chem.* **1971**, *8*, 1–74. (b) D. Holtz, *Chem. Rev.* **1971**, *71*, 139–145.
 21. K. J. Klabunde, D. J. Burton, *J. Am. Chem. Soc.* **1972**, *94*, 820–828; 5985–5990.
 22. R. Hoffmann, L. Radom, J. A. Pople, P. v. R. Schleyer, W. J. Hehre, L. Salem *J. Am. Chem. Soc.* **1972**, *94*, 6221–6223.
 23. A. Streitwieser, D. Holtz, G. R. Ziegler, J. O. Stoffer, M. L. Brokaw, F. Guibe, *J. Am. Chem. Soc.* **1976**, *98*, 5229–5234.
 24. J. H. Sleigh, R. Stephens, J. C. Tatlow, *J. Fluorine Chem.* **1980**, *15*, 411–422.
 25. Y. Apeloig, *J. Chem. Soc. Chem. Commun.* **1980**, 396–397. Y. Apeloig, Z. Rappoport, *J. Am. Chem. Soc.* **1979**, *101*, 5095–5098.
 26. A. Streitwieser, C. M. Berke, G. W. Greier, J. B. Collins, *Tetrahedron* **1981**, *37*, Suppl. 1, 345–358
 27. S. O. N. Lill, G. Rauhut, E. Anders, *Chem. Eur. J.* **2003**, *9*, 314–3153.
 28. P. v. R. Schleyer, A. J. Kos, *Tetrahedron*, **1983**, *39*, 1141–1150.
 29. R. D. Bach, R. C. Badgen, T. Lang, *J. Am. Chem. Soc.* **1979**, *101*, 2845–2848.
 30. A. D. David, T. Fukunaga, E. S. Smart, *J. Am. Chem. Soc.* **1986**, *108*, 4027–4031.
 31. W. H. Saunders Jr. *J. Org. Chem.* **1999**, *64*, 861–865.
 32. A. Pross, L. Radom, *Aust. J. Chem.* **1980**, *33*, 241–248
 33. D. S. Freidman, M. M. Francl, L. C. Allen, *Tetrahedron*, **1985**, *41*, 499–506.
 34. J. E. Bartmess, "Negative Ion Energetics Data" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, <http://webbook.nist.gov>.
 35. I. A. Koppel, R.W. Taft, F. Anvia, S.-Z. Zhu, L.-Q. Hu, K.-S. Sung, D. D. DesMarteau, L. M. Yagupolskii, Y. L. Yagupolskii, N. V. Ignat'ev, N. V. Kondratenko, A. Y. Volkonskii, V. M. Vlasov, R. Notario, P.-C. Maria, *J. Am. Chem. Soc.* **1994**, *116*, 3047–3057.
 36. J. E. Bartmess, R. D. Burnham, *J. Org. Chem.* **1984**, *49*, 1382–1387.
 37. S. A. Sullivan, J. L. Beauchamp, *J. Am. Chem. Soc.* **1976**, *98*, 1160–1165.
 38. H. J. Deyerl, L. S. Alconcel, R. E. Continetti, *J. Phys. Chem. A*, **2001**, *105*, 552–557.

39. S.T. Graul, R. R. Squires, *J. Am. Chem. Soc.*, **1990**, *112*, 2517–2529.
40. E. P. F. Lee, J. M. Dyke, C. A. Mayhew, *J. Phys. Chem. A*, **1998**, *102*, 8349–8354.
41. N. J. Rogers, M. J. Simpson, R. P. Tuckett, K. F. Dunn, C. J. Latimer, *Phys. Chem. Chem. Phys.*, **2010**, *12*, 10971–10980.
42. J.-M. M. Abboud, M. Mishima, T. Sonoda, *Proc. Estonian Acad. Sci. Chem.* **2005**, *54*(2), 60–69.
43. R. A. M. More'OFerrall, S. I. Miller, *J. Am. Chem. Soc.* **1963**, *85*, 2440–2443; R. A. M. More'OFerrall, S. I. Miller, *J. Am. Chem. Soc.* **1964**, *86*, 4016–4018.
44. G. Bianchi, O. W. Howarth, C. J. Samuel, G. Vlahov, *J. Chem. Soc., Chem. Commun.* **1994**, 627–628.
45. I. Koppel, L. A. Moretskaya, V. I. Lantvoev, J. Koppel, V. Pihl, *Organic Reactivity (Tartu)*, **1983**, *20*(4), 508–522.
46. O. Exner, *J. Phys. Org. Chem.* **1999**, *12*, 265–274.
47. V. I. Galkin, *J. Phys. Org. Chem.* **1999**, *12*, 283–288.
48. R. W. Taft, R. D. Topsom, *Prog. Phys. Org. Chem.* **1986**, *16*, 1–83.
49. K. Murata, S.-Z. Wang, Y. Morizawa, K. Oharu, *J. Fluorine Chem.* **2006**, *127*, 1125–1129.
50. J. L. Adcock, H. Luo, S. S. Zuberi, *J. Org. Chem.* **1992**, *57*, 4749–4752.
51. Md. M. R. Badal, M. Mishima, *Bull. Chem. Soc. Jpn.* **2010**, *83*, 58–65.
52. M. Zhang, Md. M. R. Badal, I. A. Koppel, M. Mishima, *Bull. Chem. Soc. Jpn.* **2013**, *86*, 813–820.
53. J. E. Bartmess and R. M. Georgiadis, *Vacuum* **1983**, *33*, 149–153.
54. K. J. Miller, *J. Am. Chem. Soc.* **1990**, *112*, 8533–8542.
55. M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery, Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N.

- Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, O. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, and D. J. Fox, *Gaussian 09*, Revision B.01, Gaussian, Inc., Wallingford CT, **2010**.
56. ORCA: F. Neese, *WIREs Comput. Mol. Sci.*, **2012**, 2, 73–78. The program package written by F. Neese, U. Becker, D. Bykov, D. Ganyushin, A. Hansen, R. Izsak, D. G. Liakos, C. Kollmar, S. Kossmann, D. A. Pantazis, T. Petrenko, C. Reimann, C. Riplinger, M. Roemelt, B. Sandhöfer, I. Schapiro, K. Sivalingam, F. Wennmohs, B. Wezislá, M. Kállay, S. Grimme, E. Valeev. def2-TZVPP: F. Weigend, M. Häser, H. Patzelt, R. Ahlrichs, *Chem. Phys. Letters* **1998**, 294, 143–152; F. Weigend, R. Ahlrichs, *Phys. Chem. Chem. Phys.*, **2005**, 7(18), 3297–3305.

Table 1. Gas-phase Acidities of Polyfluorinated Hydrocabons and Related Hydrocabons.^a Experimental Acidities and Calculated Values at the B3LYP/6-311+G(d,p)//B3LYP/6-311+G(d,p) and MP2/6-311+G(d,p)//MP2/6-311+G(d,p)

Carbon acid	GA _{exp}	GA _{calc}	
		B3LYP	MP2
CF ₃ CH ₃ (1)	376.1	371.9	376.4
(CF ₃) ₂ CH ₂ (2)	348.7 ^e	342.4 ^m	348.8 ⁿ
(CF ₃) ₃ CH (3)	326.6 ^f	319.3	326.1
(<i>i</i> -C ₃ F ₇) ₂ (C ₂ F ₅)CH (4)	313.4	307.0	313.1 ^o
1H,4H-C ₇ F ₁₀ (5) ^b	335.8 ^f	337.9	340.2
1H-C ₇ F ₁₁ (6) ^c	334.4 ^f	329.5	332.8
1H-C ₁₀ F ₁₅ (7) ^d	319.6	315.8	318.3
<i>trans-cyclo</i> -C ₄ H ₂ F ₆ (8)	344.8	335.4	340.7
<i>cis-cyclo</i> -C ₄ H ₂ F ₆ (9)	343.2	331.8	337.6
CH ₂ =CFCH ₃ (10)	372.5 ^g	372.2	375.7
CH ₂ =C(CF ₃)CH ₃ (11)	367.4 ^h	367.1	369.2
(<i>E</i>)-CF ₃ CH=CHF (12)	356.6	355.9	359.3
(<i>Z</i>)-CF ₃ CH=CHF (13)	355.5	358.0	360.4
(<i>E</i>)-CF ₃ CH=CHCl (14)	350.6	353.6	359.3
CF ₃ CHF ₂ (15)	366.8 ^g	359.4	365.2
CF ₃ CHFCHF ₂ (16)	350.5	346.3	352.6
(CF ₃) ₂ CHF (17)	347.8	341.3	348.3
CF ₃ CHFCHFC ₂ F ₅ (18)	344.0	332.4	341.7
CHCl ₂ CF ₃ (19)	348.2	346.5	353.8
CHF ₃ (20)	370.3 ^{ij}	365.7	371.9
CH ₂ F ₂ (21)	(381.2) ^{jk}	386.0	391.3
CH ₃ F (22)	400.6 ^{il}	399.3	403.3
CH ₃ CH ₃ (23)	411.7 ^j	411.0	412.3
CH ₄ (24)	409.9 ^j	407.9	410.7

^a All values in kcal mol⁻¹ (1 kcal mol⁻¹ = 4.184 kJ mol⁻¹).

^b 1H,4H-Decafluorobicyclo[2.2.1]heptane.

^c 1H-Undecafluorobicyclo[2.2.1]heptane.

^d 1H-Pentadecafluoroadamantane.

^e The value of 343.9 kcal mol⁻¹ was reported in ref. 35.

^f Ref. 15. ^g Ref. 36. ^h Ref. 37. ⁱ Ref. 38. ^j Ref. 34.

^k Ref. 39. ΔG_{acid} of 381.2 kcal mol⁻¹ seems to be too small because G2 calculation gave $\Delta H_{\text{acid}} = 399$ kcal mol⁻¹ (ref. 40) and the present MP2 also gave $\Delta H_{\text{acid}} = 399.6$ kcal mol⁻¹. Therefore, the GA value of 391.3 kcal mol⁻¹ calculated in this study was adopted in this paper rather than the experimental value in the literature.

^l Ref. 41. ^m For 2a-2, 342.9 kcal mol⁻¹ for 2a-1. ⁿ For 2a-1, 349.0 kcal mol⁻¹ for 2a-2.

^o At the MP2/def2-TZVPP level of theory on the ORCA program site.

Table 2. Calculated Gas-phase Acidities of Some Polyfluorinated Hydrocabons at the MP2/6-311+G(d,p) //MP2/6-311+G(d,p)

Carbon acid	GA _{calc}	Carbon acid	GA _{calc}
C ₂ F ₅ CH ₃ (25)	367.4	(CF ₃) ₂ C(CH ₃) ₂ (35)	384.4
C ₃ F ₇ CH ₃ (26)	364.2	(CF ₃) ₃ CCH ₃ (36)	373.6
<i>i</i> -C ₃ F ₇ CH ₃ (27)	352.7	(C ₂ F ₅) ₂ (CF ₃)CCH ₃ (37)	366.6
(C ₂ F ₅)(CF ₃)CH ₂ (28)	344.1	(<i>i</i> -C ₃ F ₇)(C ₂ F ₅)(CF ₃)CCH ₃ (38)	362.0
(C ₂ F ₅) ₂ CH ₂ (29)	337.9	CF ₃ CH ₂ F (39)	373.1
(<i>i</i> -C ₃ F ₇) ₂ CH ₂ (30)	330.7	C ₂ F ₅ CH ₂ F (40)	363.6
(C ₂ F ₅) ₃ CH (31)	313.4	C ₃ F ₇ CH ₂ F (41)	360.4
(<i>i</i> -C ₃ F ₇)(CF ₃) ₂ CH (32)	317.3	<i>i</i> -C ₃ F ₇ CH ₂ F (42)	345.2
1H-C ₈ F ₁₃ ^a (33)	327.6	(C ₂ F ₅) ₂ CHF (43)	340.4
CF ₃ CH=CH ₂ (34)	373.3	(<i>i</i> -C ₃ F ₇) ₂ CHF (44)	330.0

^a 1H-Tetradecafluorobicyclo[2.2.2]octane.

Table 3. Acidifying Effect by β -Fluorine Negative Hyperconjugation and Selected Geometry Parameters of Carbanions

Carbanion	$\Delta G(\beta\text{-F})^a$ (kcal mol ⁻¹)	$C_\beta\text{-F } (\Delta d)^b$ (Å)	$C_\alpha\text{-C}_\beta (\Delta d)^b$ (Å)	$\Sigma\theta^c$ (degree)
CF_3CH_2^- (1a)	-4.8	1.473 (0.126)	1.418 (-0.081)	338.7
$\text{C}_2\text{F}_5\text{CH}_2^-$ (25a)	-11.3	1.814 (0.453)	1.362 (-0.176)	356.8
$\text{C}_3\text{F}_7\text{CH}_2^-$ (26a)	-9.8	1.875 (0.513)	1.356 (-0.168)	357.7
<i>i</i> - $\text{C}_3\text{F}_7\text{CH}_2^-$ (27a)	-23.8	2.001 (0.619)	1.357 (-0.158)	359.3
$(\text{CF}_3)_2\text{CH}^-$ (2a-1)	-3.1	1.417 (0.078)	1.436 (-0.077)	346.1
$(\text{CF}_3)_2\text{CH}^-$ (2a-2)	-2.9	1.416 (0.070)	1.424 (-0.089)	360.0
$(\text{C}_2\text{F}_5)(\text{CF}_3)\text{CH}^-$ (28a)	-5.4	1.461 (0.107)	1.421 (-0.119)	350.9
$(\text{C}_2\text{F}_5)_2\text{CH}^-$ (29a)	-9.4	1.443 (0.088)	1.428 (-0.090)	353.5
<i>(i</i> - $\text{C}_3\text{F}_7)_2\text{CH}^-$ (30a)	-12.2	1.558 (0.184)	1.412 (-0.118)	359.3

^a Acidifying effect by β -fluorine negative hyperconjugation. Differences between GA values and the acidifying effects by the accumulated inductive effect of fluorine atoms calculated based on equation (6).

^b Relative to the corresponding neutral, positive value for enlogation.

^c Sum of angles around anion center carbon.

Table 4. Effect of α -Fluorine on Acidity and Selected Geometry Parameters of Fluorinated Carbanions

Carbanion	ΔG_A^a	$C_\alpha-F$	$(\Delta d)^b$	$C_\beta-F$	$(\Delta d)^b$	$[\Delta d]^c$	$C_\alpha-C_\beta$	$(\Delta d)^b$	$[\Delta d]^c$	$\Sigma\theta^d$	$[\Delta\Sigma\theta]^e$
CH_2F^- (22a)	-9.3	1.497	(0.108)							307.7	[-19.5]
CHF_2^- (21a)	-18.6	1.468	(0.107)							299.0	[-28.2]
CF_3^- (20a)	-39.6	1.431	(0.057)							299.7	[-27.5]
CF_3CHF^- (39a)	-3.0	1.457	(0.082)	1.414	(0.069)	[-0.016]	1.463	(-0.051)	[0.045]	305.1	[-33.6]
$CF_3CF_2^-$ (15a)	-10.9	1.436	(0.086)	1.371	(0.034)	[-0.102]	1.520	(-0.107)	[0.102]	316.3	[-22.4]
$C_2F_5CHF^-$ (40a)	-3.8	1.366	(-0.010)	2.048	(0.695)	[0.234]	1.346	(-0.192)	[-0.016]	358.5	[1.7]
$C_3F_7CHF^-$ (41a)	-3.8	1.366	(-0.010)	2.027	(0.676)	[0.152]	1.347	(-0.173)	[-0.009]	358.7	[0.8]
<i>i</i> - $C_3F_7CHF^-$ (42a)	-7.5	1.358	(-0.020)	2.111	(0.732)	[0.110]	1.346	(-0.185)	[-0.011]	359.6	[0.3]
$(CF_3)_2CF^-$ (17a)	-0.9	1.430	(0.052)	1.394	(0.056)	[-0.022]	1.467	(-0.063)	[0.043]	328.4	[-31.6]
$(C_2F_5)_2CF^-$ (43a)	2.5	1.424	(0.051)	1.432	(0.085)	[-0.011]	1.453	(-0.001)	[0.025]	335.4	[-18.1]
<i>(i</i> - $C_3F_7)_2CF^-$ (44a)	-0.7	1.378	(-0.002)	1.845	(0.475)	[0.287]	1.368	(-0.178)	[-0.044]	358.9	[-0.4]

^a $\Delta G_A = G_{A(\alpha-F)} - G_{A(\alpha-H)}$ in kcal mol⁻¹.^b Change by deprotonation in Å, positive value denotes enlongation.^c Relative to the corresponding α -H carbanion in Å, positive value denotes enlongation.^d Sum of angles around anion center carbon in degree. $\Sigma\theta = 327.2^\circ$ for CH_3^- anion.^e Relative to the corresponding α -H carbanion.

Table 5. Measured Free Energy Changes for Proton Transfer Equilibrium in the Gas Phase and Selected GA Values ^a

Carbon Acid	Reference acid	[GA] ^b	ΔG°	Selected GA
<i>(i</i> -C ₃ F ₇) ₂ (C ₂ F ₅)CH (4)	CF ₃ COOH	[316.3]	-3.0	
	(F ₃ CO) ₂ CH ₂	[310.3]	3.2	313.4
1H-C ₁₀ F ₁₅ (7)	C ₆ F ₅ OH	[320.8]	-1.2	
	CF ₃ COOH	[316.3]	3.4	319.6
CF ₃ CHFCHFC ₂ F ₅ (18)	C ₆ H ₅ CH ₂ CN	[344.1]	-0.6	
	<i>p</i> -MeC ₆ H ₄ OH	[343.4]	0.6	343.8
<i>cis</i> - <i>cyclo</i> -C ₄ H ₂ F ₆ (9)	<i>p</i> -MeC ₆ H ₄ OH	[343.5]	-0.1	
	<i>m</i> -MeC ₆ H ₄ OH	[342.7]	0.5	343.2
<i>trans</i> - <i>cyclo</i> -C ₄ H ₂ F ₆ (8)	<i>p</i> -MeC ₆ H ₄ CH ₂ CN	[345.0]	-0.2	
	<i>p</i> -MeC ₆ H ₄ OH	[343.5]	1.3	344.8
(CF ₃) ₂ CHF (17)	MeNO ₂	[349.7]	-2.0	
	CF ₃ CH ₂ CF ₃	[348.7]	-1.2	
	<i>p</i> -MeC ₆ H ₄ CH ₂ CN	[345.0]	2.8	347.8
CHCl ₂ CF ₃ (19)	CH ₃ NO ₂	[349.7]	-1.5	
	<i>p</i> -CF ₃ C ₆ H ₄ NH ₂	[346.1]	2.2	348.2
(CF ₃) ₂ CH ₂ (2)	MeNO ₂	[349.7]	-1.0	
	CF ₃ CHF ₂ CF ₃	[347.8]	1.2	
	<i>p</i> -CH ₃ C ₆ H ₄ CH ₂ CN	[345.0]	3.0	348.7
CF ₃ CHFCHF ₂ (16)	(<i>E</i>)-CF ₃ CH=CHCl	[350.6]	-0.2	
	<i>m</i> -FC ₆ H ₄ CH ₂ OH	[350.8]	-0.3	
	MeNO ₂	[349.7]	0.8	350.5
(E)-CF ₃ CH=CHCl (16)	<i>m</i> -FC ₆ H ₄ CH ₂ OH	[350.8]	-0.2	
	MeNO ₂	[349.7]	0.9	350.6
(Z)-CF ₃ CH=CHF (13)	<i>p</i> -MeC ₆ H ₄ COCH ₃	[354.9]	0.6	
	CF ₃ CH ₂ OH	[354.1]	1.4	355.5

<i>(E)</i> -CF ₃ CH=CHF (12)	<i>p</i> -MeC ₆ H ₄ COCH ₃	[354.9]	1.6	
	C ₆ H ₅ COCH ₃	[354.5]	1.9	356.5
CF ₃ CH ₃ (1)	<i>p</i> -CH ₃ C ₆ H ₄ CH ₃	[374.8]	1.3	376.1

^a All values are given in kcal mol⁻¹.

^b Taken from the literature ref. 34.

Graphical Abstract

Gas-phase Acidity of Polyfluorinated Hydrocarbons. Effects of Fluorine and the Perfluoroalkyl Group on Acidity

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Gas-phase acidities of polyfluorinated hydrocarbons have been determined by measuring proton-transfer equilibria and by computing free energies of deprotonated carbanions and the neutrals. Effects of fluorine and the perfluoroalkyl group on acidity have been investigated.