A DFT study on the origin of the fluorine *gauche* effect in substituted fluoroethanes

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ABSTRACT

DFT derived conformational energy profiles of a series of β-substituted α-fluoroethanes ($F–CH_2CH_2–X$) have been explored where the substituent X was varied as NH_3^+, OCOH, NCO, NO_2, NHCHO, F, N_3, CH=NH, NCS, CH=C=CH$_2$, CH$_3$, CH=CH$_2$, NC, CN, CHO, and CCH. Comparisons were correlated relative to 1,2-difluoroethane, a compound which exhibits a well known *gauche* preference. Only four of the compounds displayed an *anti* preference, with the large majority preferring a *gauche* conformation. In particular the influence of steric and electrostatic attraction/repulsion between the fluorine atom and the X-substituent was explored by evaluating rotational energy profiles for all compounds and separately NBO correlations were evaluated to assess the contribution of hyperconjugation to the minimised *gauche* and *anti* conformers. In the event the *gauche* preference for 1,2-difluoroethane was shown to have an origin due largely to σ(C–H)→σ*(C–F) hyperconjugative interactions, whereas the conformational preference for the remaining structures is rationalised by hyperconjugative as well as steric and electrostatic contributions. The *anti* preferred compounds **13**, **14** and **16** possessed triple bonds and the preference arose due to fluorine/*p*-orbital repulsion.

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1. Introduction

The influence of fluorine on the conformation of organic molecules is generally rationalised by the electrostatic and stereoelectronic influence of the fluorine atom rather than its size.[1] The C–F bond[2] is the most polarised in organic chemistry and possesses a large dipole, which interacts electrostatically with other polar substituents. The most widely described stereoelectronic phenomenon associated with the C–F bond is a hyperconjugative interaction with a vicinal C–H bond. In such interactions the C–H bond is the donor (HOMO) and the C–F σ* antibonding orbital (LUMO) is the acceptor.[3] Such hyperconjugative effects have been used to rationalise the *gauche* conformation for 1,2-difluoroethane,[4] which is unexpectedly lower in energy than its *anti* conformer. β-Fluoroesters[5a,b] and amides[5a–d] F–CH$_2$–CH$_2$–X–C(O)R also exhibit *gauche* preferences, as do fluoroethanol and fluoroethylamine, however in the latter two cases the overall structures are dominated by intramolecular hydrogen bonding interactions.[6] A particularly strong *gauche* effect has been observed in the case of β-fluoroethylammonium ions,[7] where the ammonium group carries a formal positive charge. A large *gauche* preference is observed which arises now due to a strong charge-dipole interaction

between the fluorine atom and the ammonium group, and thus this *gauche* preference is electrostatic in origin, rather than stereoelectronic[7] (see Fig. 1).
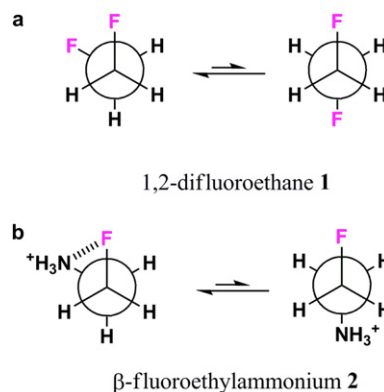

Figure 1. The *gauche* preferences for (a) 1,2-difluoroethane **1** and (b) β-fluoroethylammonium **2**. The former is largely stereoelectronic (σ(C–H)→σ*(C–F)) in origin, whereas the latter is largely electrostatic (charge–dipole interaction) in origin.

As a consequence the *gauche-anti* energy difference is large. In order to extend our understanding of the origin of *gauche* preferences, a series of β-substituted α-fluoroethanes ($F–CH_2CH_2–X$) have

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been subjected to a density functional theory (DFT)[8] investigation. The substituent X was varied widely as NH_3^+, OCOH, NCO, NO_2, NHCHO, F, N_3, CH=NH, NCS, CH=C=CH$_2$, CH$_3$, CH=CH$_2$, NC, CN, CHO, and CCH. Full rotational energy profiles have been evaluated to explore the effects of steric/electrostatic interactions in the *gauche* and *anti* conformers. Electrostatic contributions have also been explored using partial atomic charges. For each conformer, molecular orbital analyses based on the NBO[9] approach has been carried out to evaluate the significance of hyperconjugative interactions in the individual systems.

2. Computational details

Compounds (F–CH$_2$CH$_2$–X) **1–16** were considered where X=NH_3^+, OCOH, NCO, NO_2, NHCHO, F, N_3, CH=NH, NCS, CH=C=CH$_2$, CH$_3$, CH=CH$_2$, NC, CN, CHO, and CCH. The *gauche* and *anti* conformers of each compound were fully optimised at the DFT level using the 6-311+G(d,p) basis set[14] and the B3LYP functional, which consists of a hybrid Becke+Hartree–Fock[8] exchange and the Lee–Yang–Parr[10] correlation functional with nonlocal correction. The M05-2X[11] functional has also been used, which is a hybrid meta DFT functional. Dipole moments and charges were derived from the DFT calculations. The compounds were ordered in terms of their *gauche* preference by calculating the energy difference between their minimum *gauche* and *anti* conformers (see Table 1).

Mulliken[12] and Natural Bond Order[9] (NBO) charges have been calculated for individual atoms, and through-space distances have been evaluated for the minimised conformations. Potential energy curves were evaluated by allowing a progressive 10° rotation around the central FC–CX bond. This was the only constraint applied, and each calculation allowed the X-substituent to minimise. For systems in which substituent X possesses an axis of symmetry projecting along the C–X bond, e.g. X=NH_3^+, CN, NC, then conformational minimisation in those cases was not important. However for the remaining non linear systems where X=NCO, NCS, NO_2, OCOH etc., this minimisation is an important aspect of the system.

Natural bond orbital analysis (NBO)[9] was applied to analyse bond–bond electron distributions in more detail. All calculations have been carried out using the Gaussian 03 program package.[13]

3. The Results and discussion

Rotational energy profiles. Rotational energy profiles were evaluated for compounds **1–16**. The data is presented fully in the

Supplementary data, but for brevity only the profiles of **1** X=F, **2** X=NH_3^+, and **14** X=CN are shown in Figure 2. It can be seen that rotational energy minima are found only at torsion angles of approximately 60°, 300° (*gauche* conformers) and 180° (*anti* conformer). The two rotational energy minima for **1** X=F and **2** X=NH_3^+, confirm a *gauche* preference whereas the *anti* conformer is favoured for **14** X=CN.[15] For the systems where the X-groups are not linear beyond the C–X bond, e.g. **7** X=NCO,[16] **4** X=NO_2,[15a] **9** X=NCS, etc., rotational energy profiles were evaluated allowing only rotation along the C–X bond, but otherwise constraining the molecule in either a minimised *gauche* or *anti* conformation. This experiment was carried out in each case (See Supplementary data) to explore the influence of rotating the X-group. Figures 3 and 4 illustrate the results generated for **4** X=NCO and **5** X=NO_2, respectively.
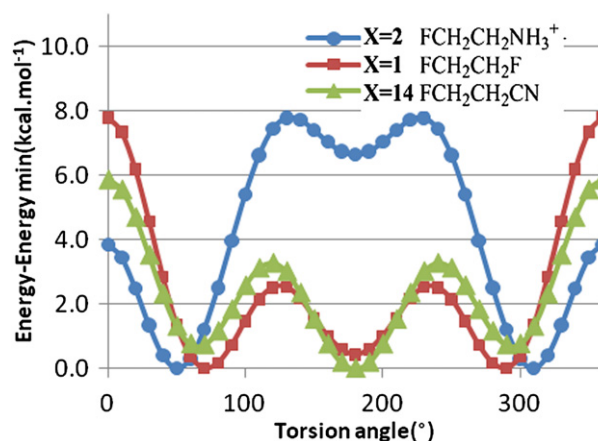

Figure 2. Energy profile for 1,2-difluoroethane **1** (*gauche* favoured), fluoro-ethylammonium **2** (*gauche* favoured) and 1-fluoro-2-cyanoethane **14** (*anti* favoured).

For the *anti* conformer of the isocyanate **7** (X=NCO) in Figure 3, the rotational energy profile is symmetrical, where the energy is raised as the isocyanate group gets sterically close to the vicinal hydrogen atoms. There is a clear minimum when the F–C–C–X torsion angle is 180° (isocyanate pointing away from the fluorine atom), minimising steric and electrostatic repulsion. In the case of the *gauche* structure however the rotational energy profile shows a more extreme peak and trough. The highest point (260°) on the profile results from fluorine–nitrogen lone pair repulsion, and the

Table 1

X	Δ energy[a] *gauche-anti* (kcal/mol) B3LYP	Δ energy[a] *gauche-anti* (kcal/mol) M05-2X	Preferred[b] conformer	Δ dipole[c]
2 NH_3^+	−6.65	−7.37	s *gauche*	NA
3 OCOH	−1.40	−2.18	s *gauche*	4.94
4 NO_2	−1.22	−1.12	s *gauche*	4.42
5 NHCOH	−1.00	−1.12	s *gauche*	4.53
1 F	−0.82	−0.66	s *gauche*	3.02
6 N_3	−0.76	−1.21	s *gauche*	3.42
7 NCO	−0.74	−1.06	s *gauche*	3.97
8 CHNH	−0.25	−0.65	s *gauche*	3.62
9 NCS	−0.20	−0.24	w *gauche*	4.09
10 CHCCH$_2$	−0.19	−0.34	w *gauche*	2.00
11 CH$_3$	−0.18	−0.35	w *gauche*	2.11
12 CHCH$_2$	−0.01	−0.17	w *gauche*	1.95
13 NC	0.25	0.31	w *anti*	4.53
14 CN	0.64	0.64	s *anti*	4.68
15 CHO	0.84	1.20	s *anti*	3.82
16 CCH	0.98	1.03	s *anti*	2.18

[a] Energy differences between the *gauche-anti* conformers of F–CH$_2$CH$_2$X **1–16** calculated for minimised structures.
[b] The lowest energy conformer, (s: strong, w: weak).
[c] Difference in the dipole moment of the *gauch-anti* conformer in Debye. NA = Not applicable.
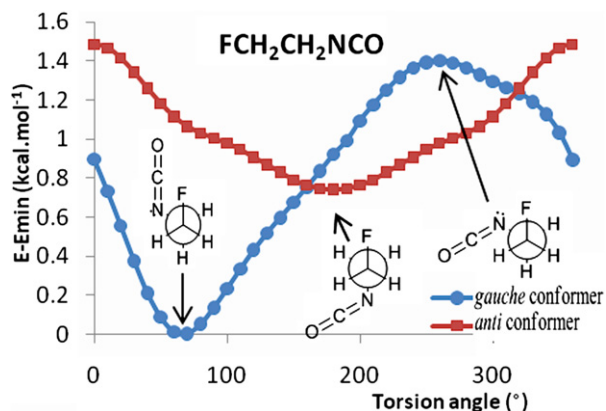
Figure 3. Energy profile of 1-fluoro-2-isocyanatoethane **7** where the isocyanate group is rotated in both the minimised *gauche* (●) and *anti* (■) conformers.
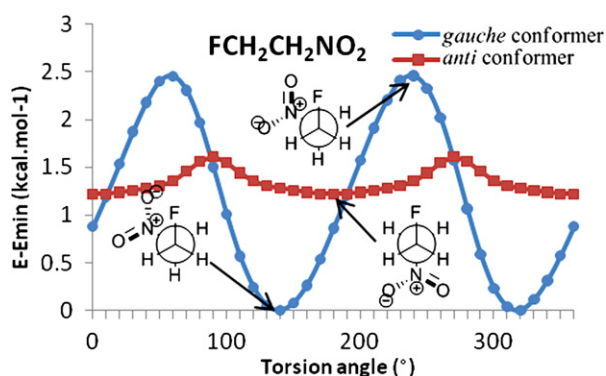

Figure 4. Rotational energy profile for the minimised *gauche* (●) and *anti* (■) conformers of 1-fluoro-2-nitroethane **4**, exploring nitro group rotation.

lowest energy conformer (65°) has the C–F bond and the isocyanate groups co-aligned. This conformer has a relatively large dipole (3.7 D) but nitrogen lone pair repulsion is minimised and this global minimum may benefit from an electrostatic interaction between the isocyanate carbon and the fluorine atom (see Fig. 5). The rotational energy profiles of the *gauche* and *anti* constrained conformers for the nitro compound **4** are superimposed in Figure 4. Similar to isocyanate **7**, the rotational energy profile for the *anti* conformer of **4** does not change much due to a relatively small steric repulsion between the oxygen atoms of the nitro group and the fluoromethylene hydrogens. This is a symmetrical profile. Although the calculated dipole (1.75 D) is lower in the *anti* conformers with the polar substituents pointing in opposite directions, this is not a determining factor in favouring a conformer. For the *gauche* conformer of **4** the rotational energy profile is more dramatic with strong electrostatic repulsion when the nitro oxygen atoms approach the fluorine atom, raising the energy above the *anti* conformer. However the minimum energy *gauche* conformers (140°, 320°) benefit from an antiparallel dipolar interaction between one of the nitro $N^{\delta+}$–$O^{\delta-}$ bonds and a fluoromethylene $^{\delta-}$FC–$H^{\delta+}$ bond, and possibly an electrostatic attraction between the fluorine and the electropositive nitrogen (see Fig. 5).

Table 1 summarises the DFT derived minimised energies of the *gauche* and *anti* conformers as obtained from the rotational energy data described above and elaborated fully in the Supplementary data. B3LYP was the primary method, but MO5-2X was included for comparison. In the event the resultant *gauche-anti* energies and trends are similar and demonstrate that the outcome is not dependent on the functional. Dipole moments of

the minimised structures are also presented in Table 1 (except for charged species **2**).

A cursory analysis of the $\Delta_{gauche-anti}$ energy column (B3LYP) reveals three groupings within Table 1. Compounds **1**–**7** are clearly *gauche* preferred (>-0.74 kcal mol^{-1}), compounds **8**–**13** show only a weak preference either way (±0.25 kcal mol^{-1}), and compounds, **14** X=CN[15], **15** X=CHO and **16** X=CCH[17] are clearly *anti* preferred ($>+0.63$ kcal mol^{-1}). The top of Table 1 identifies the 2-fluoroethylammonium **2** cation as having the greatest *gauche* preference at 6.65 kcal mol^{-1}, much greater than any other system studied. The magnitude favouring this conformational preference has previously been noted and is associated with its formal charge.[7] The outcome also reinforces the *gauche* preference for 1,2-difluoroethane **1** with a magnitude similar to previous studies[4] and the experimental value of 0.798 kcal mol^{-1}.[3e]

Molecular dipole moments have been calculated for all of the minimised *gauche* and *anti* conformers. In general the larger dipole moments remain associated with the *gauche* structures. Thus minimising the dipole moment is not the determining factor in establishing the preferred conformer. In all of the clearly *gauche* preferred structures **1**–**7** the first atom of the X-group is a heteroatom. One immediate consequence of this is that the C–X bond is polarised and can accommodate $\sigma(C–H)\rightarrow\sigma^*(C–X)$ hyperconjugation, which will contribute stabilisation to the *gauche* conformer. This is discussed more fully in the context of the NBO calculations described below. Also in these cases there is an electropositive atom in X carrying a partial positive charge (calculated Natural charges[9]) in relatively close proximity to the fluorine atom, supporting an electrostatic interaction. These are the ammonium hydrogens (+0.455) of **2**, the carbonyl carbon (+0.661) of **3**, the isocyanate carbon (+0.846) of **7**, the nitro nitrogen (+0.487) of **4**, the amide hydrogen (+0.403) of **5** and the central azide nitrogen (+0.229) in **6** as illustrated in Figure 5. Also it was highlighted above that the nitro conformer **4** gets additional stabilisation by an antiparallel dipolar interaction between a nitro $N^{\delta+}$–$O^{\delta-}$ and a fluoromethylene $^{\delta-}$FC–$H^{\delta+}$ hydrogen.[18,19] Where the heteroatom has a lone pair such as oxygen in **3** or nitrogen in **6** and **7**, then the lone pair is turned away from the fluorine in the *gauche* structures, minimising electrostatic repulsion. Compounds **8**–**12** show only a weak *gauche* preference. Notably only one of these, X=NCS **9**, has a heteroatom as the first atom of the X-group, thus the C–^{X}C bonds are less polarised relative to **1**–**7** and less able to accommodate a stabilising $\sigma(C–H)\rightarrow\sigma^*(C–X)$ hyperconjugative interaction. It is perhaps useful to compare isocyanate **7**, which has a greater *gauche* preference, to isothiocyanate **9**. Isocyanate **7** has a much larger +ve Natural charge (+0.846 versus +0.230) on the central carbon atom and the F⋯C distance is much shorter in the isocyanate (3.13 Å versus 3.69 Å), indicative of a stronger electrostatic interaction.

The cases of compounds X=NC **13**, X=CN **14**, X=CHO **15** and X=CCH **16** are noteworthy relative to the other systems studied, in that they prefer to adopt *anti* rather than *gauche* conformers. All of these *anti* conformers have lower molecular dipole moments than their *gauche* conformers (Table 1), however it is difficult to attach a particular significance to this observation given that this is also the case for most of the *gauche* preferred structures, where the *anti* conformers have larger dipoles. Three of these compounds **13**, **14** and **16** have sp hybridised X-substituents and clearly p-orbital repulsion with the fluorine lone pairs will favour the *anti* conformer. There are no examples of an sp hybridised X-group with a *gauche* preference, and this appears to be a determining factor. The electrostatic surface potential maps in Figure 6 of the *gauche* and *anti* conformers of these *anti* preferred systems help visualise the electrostatic repulsion in the *gauche* conformers, and the relative relaxation in the *anti* conformers.

Compound **13** has a C–^{X}N bond, the only one of this group carrying such a heteroatom but it is only weakly *anti* favoured. p-
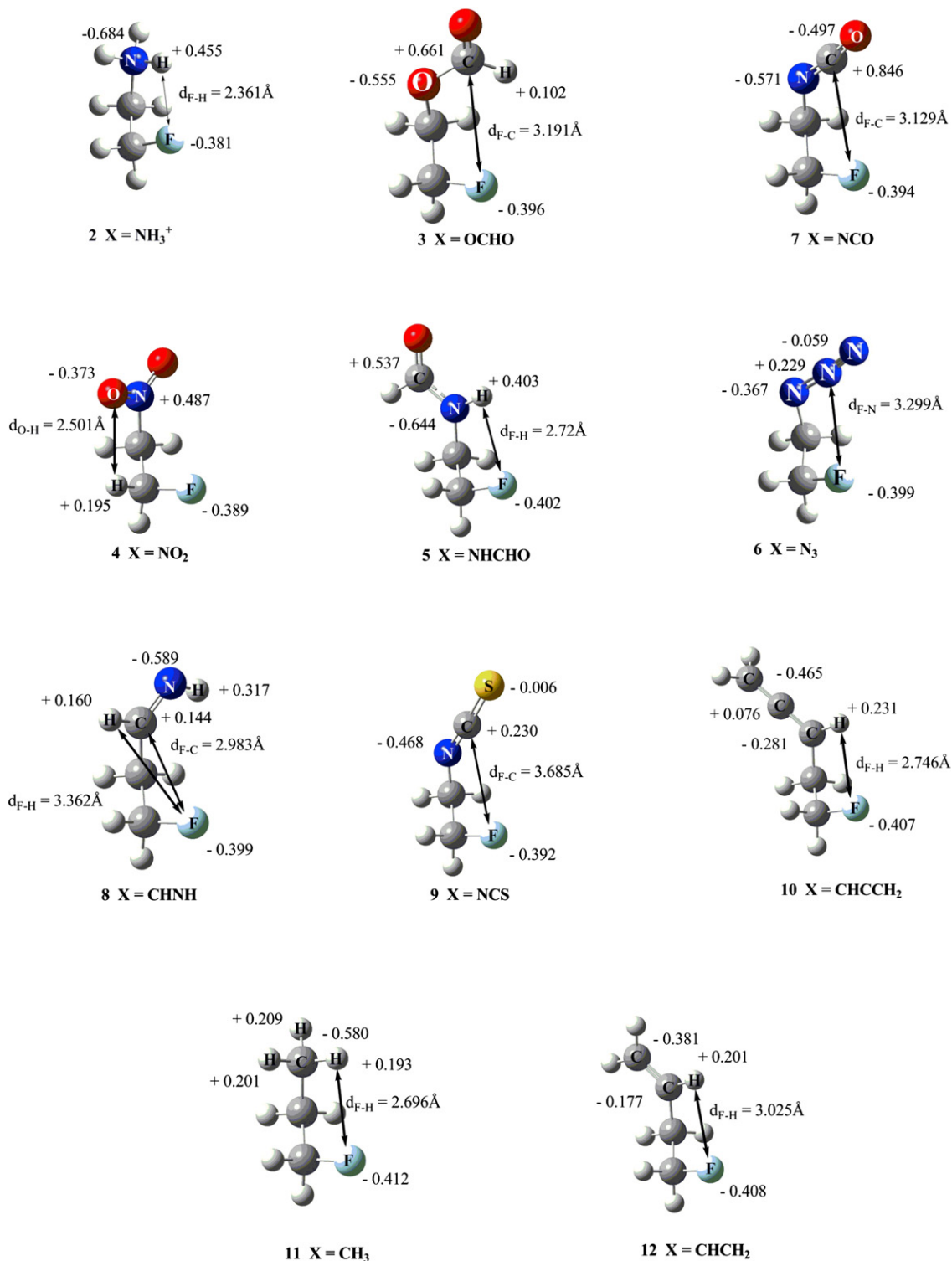
Figure 5. Minimised *gauche* structures with putative electrostatic interactions (double headed arrows) between selected atoms. The distance d is given between selected atoms. Selected Natural atomic charges are given with their respective signs.

Orbital repulsion favouring the *anti* structure for **13** is being countered by a $\sigma(C–H)\rightarrow\sigma^*(C–N)$ hyperconjugation interaction favouring the *gauche* structure, thus compromising the magnitude of the *anti* preference relative to **14** and **16**. In the case of **16**, where there are no heteroatoms X=CCH, then there is a maximum *anti* preference due to maximum F⋯p-orbital repulsion. Finally compound **15** where X=CHO is a special case relative to the other *anti* preferred structures. Analysis of the favoured *anti* conformer

(Fig. 6) reveals a short and presumably stabilising antiparallel dipolar $C{=}O^{\delta-}{\cdots}^{\delta+}HCF^{\delta-}$ contact (2.389 Å) similar to that observed in the *gauche* conformer of **4** X=NO$_2$.

Natural Bond Orbital studies. NBOs studies[9] were carried for compounds **1–16**. The focus was to determine relative hyperconjugative electron distributions between bonding and *anti* bonding orbitals, interactions, which can contribute to stabilisation of individual conformers.[3]
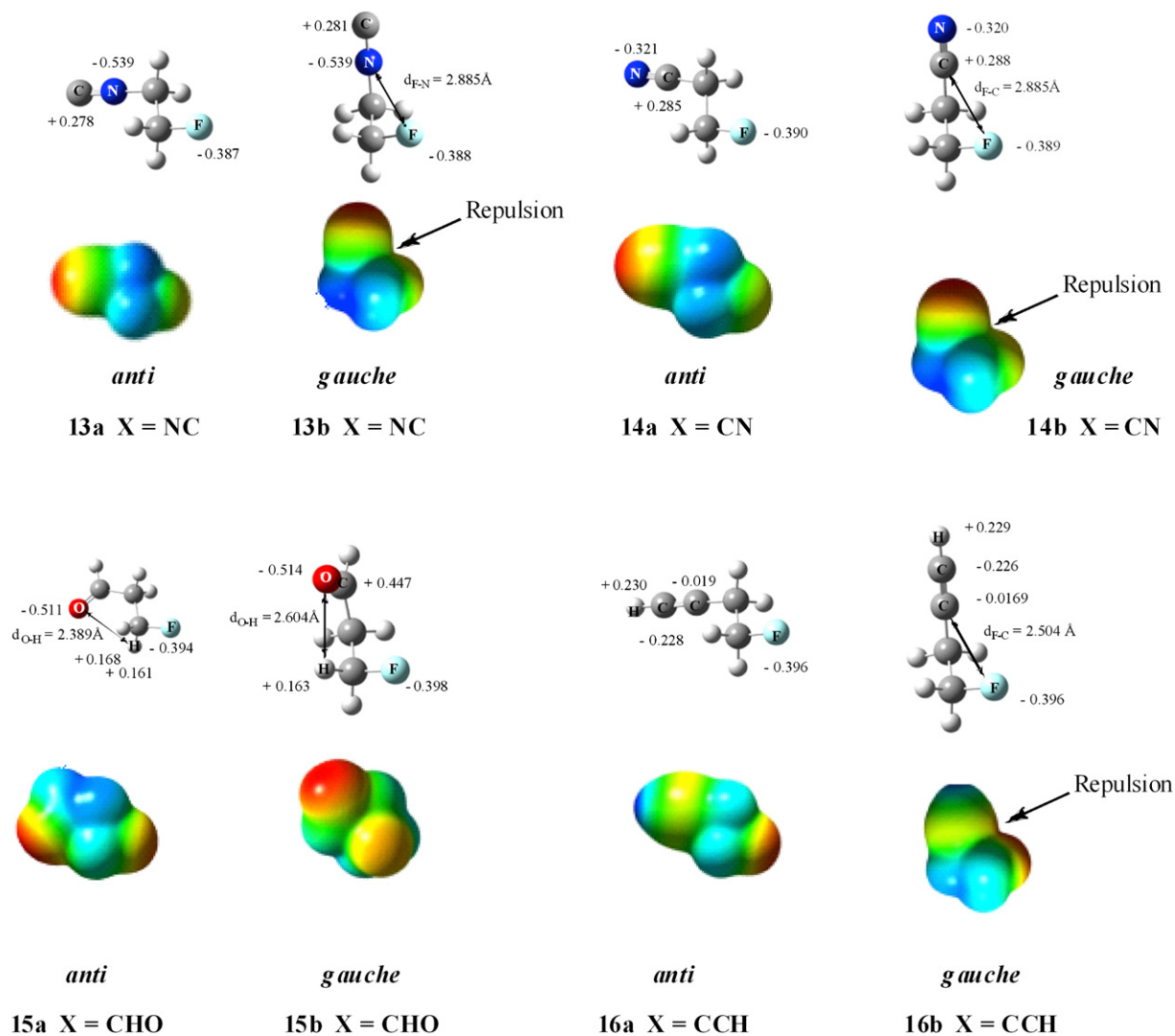
Figure 6. Minimised *anti* and *gauche* structures of compounds **13**–**16** showing selected bond distances and atomic natural charges. In these four cases the *anti*-conformer is the preferred. The *gauche* conformers appear to be destabilised relative to the *anti* conformers due to a close proximity of the fluorine atom to the first *sp* hybridised atom of the X-substituent. Electrostatic potential surface maps are illustrated for each minimised conformer which helps highlight areas of repulsion.

Each *gauche* and *anti* conformer was minimised as previously described by DFT at the B3LYP 6-311+g(d,p) level. In this way all of the molecules **1**–**16** were investigated. For brevity only the data for isocyanate **7** is shown (Table 2). The remaining data for **1**–**6** and **8**–**16** are provided in the Supplementary data.

The interaction energies ($\Delta E_{\sigma\sigma}$) around the C–C bond are relatively constant in the case of the minimised *anti* conformer, however for the *gauche* conformer electron transfer between $\sigma(C_1–H_a)\rightarrow\sigma^*(C_2–F)$ and $\sigma(C_2–H_c)\rightarrow\sigma^*(C_1–N)$ is significantly stabilising. The overall values for the global NBO interactions within the *anti* and *gauche* conformers of molecule **1**–**16** are presented in Table 3.
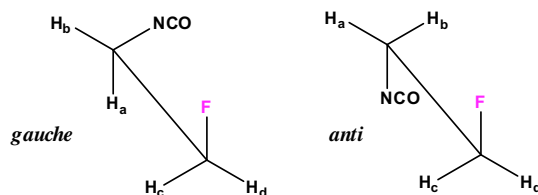
The largest Δ Global hyperconjugative stabilisation is found for 1,2-difluoroethane[4a,e] **1** with an overall difference value between the *gauche* and *anti* conformers of 4.04 kcal mol^{-1}, in favour of the *gauche* conformer. The most significant contributor is the $\sigma(C–H)\rightarrow\sigma^*(C–F)$ interaction (4.67 kcal mol^{-1}, Table 4). This is consistent with hyperconjugation as the major contributor to the *gauche* preference for 1,2-difluoroethane **1**. Values are tabulated for all molecules **1**–**16** in Table 4. In contrast 2-fluoroethylammonium **2**, which has the largest *gauche* preference, has a very low global hyperconjugative contribution to this

stabilisation (2.57 kcal mol^{-1}, Table 3). It is already established that the *gauche* preference in this case is due to an electrostatic charge-dipole origin between the fluorine and the ammonium group.[7] For those molecules that display a larger *gauche* preference than 1,2-difluoroethane **1**, it emerges that the calculated NBO Δ Global interaction is lower than for 1,2-difluoroethane **1** (Table 3). This forces the conclusion that the increased stabilisation must derive from another source in those cases, and most probably is electrostatic in origin, due to the various interactions discussed above and illustrated in Figure 5. Thus the overall stabilising effect arises from a combination of hyperconjugative and electrostatic effects. The relative impact of these contributors changes depending on the different functional groups.

The data presented in Table 3 illustrate the sum of all of the hyperconjugative interactions; however it is interesting to distil the most significant contribution. The major factor that emerges is the capacity of the $\sigma^*(C–F)$ orbital and $\sigma^*(C–X)$ orbital to accept electron density (act as a LUMO) from stereoelectronically aligned C–H donor bonds (HOMO's). This is illustrated by the hyperconjugation values; $\sigma(C–H)\rightarrow\sigma^*(C–F)$ and $\sigma(C–H)\rightarrow\sigma^*(C–X)$ for the *gauche* conformations of **1**–**16** in Table 4.

Table 2

Contribution of the NBO interaction energies to the global interactions (see Table 3) around the C_1–C_2 bond for the minimised *gauche* (upper) and *anti* (lower) conformers for isocyanate **7**. $\Delta E_{\sigma\sigma}$ is the magnitude of the NBO interaction in kcal mol^{-1}, ε_{σ^*}–ε_{σ} is the difference in energy between the two interacting bonding and antibonding orbitals in Hartrees and F is the effective orbital Hamiltonian (Fock or Kohn–sham operator) also in Hartrees

	CH$_2$FCH$_2$NCO *gauche*		
	$\Delta E_{\sigma\sigma}$(kcal.mol^{-1})	ε_{σ^*}-ε_{σ}(Hartrees)	$F_{\sigma\sigma^*}$(Hartrees)
σ (C_1–H_a)–σ* (C_2–F)	4.63	0.74	0.052
σ (C_1–N)–σ* (C_2–H_C)	0.85	1.12	0.028
σ (C_1–H_b)–σ* (C_2–H_d)	2.28	0.89	0.04
σ (C_2–H_c)–σ* (C_1–N)	3.7	0.89	0.051
σ (C_2–F)–σ* (C_1–H_a)	0.92	1.3	0.031
σ (C_2–H_d)–σ* (C_1–H_b)	2.42	0.91	0.042
Total	14.80		
	CH$_2$FCH$_2$NCO *anti*		
	$\Delta E_{\sigma\sigma}$(kcal mol^{-1})	ε_{σ^*}–ε_{σ}(Hartrees)	$F_{\sigma\sigma^*}$(Hartrees)
σ (C_1–N)–σ* (C_2–F)	1.48	0.99	0.034
σ (C_1–H_a)–σ* (C_2–H_d)	2.12	0.89	0.039
σ (C_1–H_b)–σ* (C_2–H_c)	2.12	0.89	0.039
σ (C_2–F)–σ* (C_1–N)	1.45	1.28	0.039
σ (C_2–H_d)–σ* (C_1–H_a)	2.23	0.9	0.04
σ (C_2–H_c)–σ* (C_1–H_b)	2.23	0.9	0.04
Total	11.63		

As expected for the *gauche* conformers, the X-substituent has limited impact on the σ(C–H)→σ*(C–F) interaction. This latter interaction is large and relatively uniform for all of the systems studied. Only in the case of **2** where X=NH$_3^+$ is this interaction weakened, most probably because of the large −ve inductive effect, which decreases the electron density of the C–H bond. On the other hand alkane **11** and alkene **12** have less polar X-groups and therefore, the donor capacity of these C–H bonds and this interaction, is maximal. For the other systems evaluated σ(C–H)→σ*(C–X) donation is much more varied and generally reduced relative to the σ(C–H)→σ*(C–F) interaction due to the changing nature of the X-groups. The more electronegative X the better this interaction. In terms of the first atom of the various X-substituents the hyperconjugative order decreases consistent with electronegativity X=F>O>N>C.

Hyperconjugative interactions are much reduced overall in the *anti* conformers, with *anti peri*-planar C–F and C–X bonds. The σ(C–F)→σ*(C–X) and σ(C–X)→σ*(C–F) interactions add no significant stabilisation to these conformers (See Supplementary data). For the *anti* favoured molecules hyperconjugative interactions between the p-orbital of the triple bond and the σ*(C–F) orbitals were investigated for **13**, **14** and **16**, see Table 5, as a potential stabilising interaction. NBO analysis does indicate a weak interaction in all cases (0.61–0.97 kcal mol^{-1}). Perhaps more significant, for stabilisation of the *anti* conformer, is the σ(C–X)→σ*(C–F) interaction. In the cases of **14** and **16**, where the first atom of X=C, then there is a significant interaction, however this is reduced in the case of **13**, where the first atom of X=N, and thus the increased electronegativity reduces hyperconjugation.

Table 3

Sum of the total NBO interactions around the C_1–C_2 bond for the minimised *gauche* and *anti* conformers of **1–16**

X	NBOs Global interaction		
	Gauche(kcal mol^{-1})	*Anti*(kcal mol^{-1})	Δ Global interaction *gauche-anti*
2 NH$_3^+$	13.96	11.39	2.57
3 OCOH	14.9	11.46	3.44
4 NO$_2$	14.96	11.83	3.13
5 NHCHO	14.55	13.53	1.02
1 F	**15.16**	**11.12**	**4.04**
6 N$_3$	14.73	11.97	2.76
7 NCO	14.80	11.63	3.17
8 CHNH	15.06	12.94	2.12
9 NCS	14.26	11.59	2.67
10 CH=C=CH$_2$	15.11	14.35	0.76
11 CH$_3$	16.09	14.15	1.94
12 CH=CH$_2$	14.23	13.61	0.62
13 NC	14.14	11.23	2.91
14 CN	13.82	12	1.82
15 CHO	15.21	12.78	2.43
16 CCH	14.4	12.41	1.99

Table 4

σ(C–H)→σ*(C–F) and σ (C–H)→σ*(C–X) NBO interactions for the minimised *gauche* conformers of **1–16**

X	*Gauche* conformers	
	σ(C–H)→σ*(C–F)(kcal mol^{-1})	σ(C–H)→σ*(C–X)(kcal mol^{-1})
2 NH$_3^+$	3.33	4.3
3 OCOH	4.44	4.25
4 NO$_2$	4.18	4.39
5 NHCHO	4.38	3.66
1 F	**4.67**	**4.67**
6 N$_3$	4.59	3.61
7 NCO	4.63	3.7
8 CHNH	4.86	2.99
9 NCS	4.5	3.8
10 CH=C=CH$_2$	4.77	3.09
11 CH$_3$	5.21	3.27
12 CH=CH$_2$	5.24	3.42
13 NC	4.23	4.02
14 CN	4.18	3.09
15 CHO	4.84	2.96
16 CCH	4.56	3.25

Table 5
$\sigma(C–X_1) \rightarrow \sigma^*(C–F)$ and $\pi (X_1–X_2) \rightarrow \sigma^*(C–F)$ NBO interactions for the *anti* conformers

X		$\Delta E\sigma\sigma$ (kcal mol^{-1})	$\varepsilon_{\sigma^*} - \varepsilon_{\sigma}$ (Hartrees)	$F_{\sigma\sigma^*}$ (Hartrees)
13 NC	$\sigma(C_1-N) \rightarrow \sigma^*(C_2-F)$	1.35	1.05	0.034
14 CN	$\sigma(C_1-C) \rightarrow \sigma^*(C_2-F)$	2.04	0.94	0.039
15 CHO	$\sigma(C_1-C) \rightarrow \sigma^*(C_2-F)$	2.5	0.87	0.042
16 CCH	$\sigma(C_1-C) \rightarrow \sigma^*(C_2-F)$	2.06	0.91	0.039
13 NC	$\pi (N-C_N) \rightarrow \sigma^*(C_2-F)$	0.97	0.58	0.021
14 CN	$\pi (C_N-N) \rightarrow \sigma^*(C_2-F)$	0.61	0.56	0.016
16 CCH	$\pi (C_C-C_H) \rightarrow \sigma^*(C_2-F)$	0.84	0.5	0.018

4. Conclusion

This study has explored the relative energies of the *gauche* and *anti* conformers of fluoroethanes **1**–**16** ($FCH_2–CH_2X$) by DFT calculations. Full rotational energy profiles were evaluated, exploring conformational energies about the central C–C bonds and also rotation of the C–X bonds. Dipole moments of all minimised conformers were calculated, however this was not a determining factor in identifying the favoured conformer (*gauche* or *anti*). The rotational energy profiles revealed key steric and electrostatic interactions, which influence the favoured conformers in each case. In particular the lone pairs of the heteroatoms (O/N) of the X-groups avoid close contact to the fluorine atom, due to electrostatic repulsion. The dipole of the C–F bond can orient towards electropositive atoms of the X-substituent, and this emerged as a contributing stabilising interaction in several systems (e.g., **3** X=OCHO, **7** X=NCO, **6** X=N$_3$, **9** X=NCS). NBO analysis was used to identify significant stereoelectronic interactions in all of the systems **1**–**16** and provided a useful insight into key hyperconjugative interactions. The $\sigma(C_1-H) \rightarrow \sigma^*(C_2-F)$ and $\sigma(C_2-H) \rightarrow \sigma^*(C_1-X)$ interactions emerge as important, when these bonds are antiperiplanar to each other, a situation that arises in all *gauche* conformers. The stabilisation associated with the latter interaction increases with increasing electronegativity of the X-substituent.

At the outset 1,2-difluoroethane **1** was a reference molecule where the *gauche* conformer is stabilised significantly by hyperconjugation, and fluoroethylammonium **2**, was used as a system stabilised significantly by electrostatic interactions. This was borne out in the study, and the remaining systems studied showed intermediate behaviour with both electrostatic/hyperconjugative effects contributing to conformer stability. Four systems (**13**–**16**), had an *anti* conformer preference. Three of these had an sp hybridised X-group. Electrostatic repulsion between the fluorine and the p-orbital of the triple bond is clearly destabilising the *gauche* conformers in these cases, and the NBO study revealed the $\sigma(C-X_1) \rightarrow \sigma^*(C-F)$ hyperconjugative interaction contributing stability to these *anti* conformers, particularly for **14**, **15** and **16** where the first atom of the X-substituent is carbon, with a low electronegativity.

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Supplementary data

Details of rotational energy profiles and complete NBO interactions for **1**–**16** are given in full. Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tet.2010.01.049.

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