Molecular Mechanics of Organic Halides. Part 6.[1] Modified Del Re Electrostatics and the Force Field

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Del Re's method of calculating the charge distribution in saturated molecules is re-examined and modified, by incorporating field effects and by accounting for contracted bond lengths. The ensuing procedure, simple and rapid, is made the basis for calculating the electrostatic term in the molecular mechanical force field. Improvement is gained over previous force fields for organic halides, but some problems remain. Notable among these is the difficulty to define a set of constants that fits 1-halogenopropanes and, simultaneously, cyclic halides and certain derivatives of 1-halogenopropanes.

IN molecular mechanics, the energy of a molecule is expressed as a sum of contributions, where each contribution accounts for a given type of strain and is a function of appropriate internal co-ordinates.[2,3] If the molecule contains more than one strongly dipolar bond, as in organic di- and poly-halogenoalkanes, the intramolecular electrostatic interaction (E_{es}) counts among these contributions. In practice, one either assigns moments to various bonds and obtains E_{es} by the formalism of dipole–dipole interaction (' dipole approach '), or distributes charges among atoms and expresses E_{es} as a pairwise sum of Coulomb energies, $E_{es} = \Sigma Q_iQ_j/R_{ij}$ (' monopole approach '). Ways to apportion charges have been reviewed;[3,4] more current are the quantum-chemical CNDO/2 [5] and the semiclassical Smith–Eyring [6] (SE) or the Modified Smith–Eyring [7] (MSE) procedures.

In this paper we call attention to another procedure,[8] devised by Del Re in 1958 and as yet unexplored in molecular mechanics. We consider it to have both a practical and a conceptual advantage over currently used techniques. Unlike the computation of overlap populations by CNDO/2, Del Re calculations are very rapid, as befits a preliminary stage to the rapid force field optimization. And, unlike SE and MSE, the method is ' transparent ', that is, the underlying principles do not get blurred in the passage from theory through parametrization to actual application.

Del Re's method (hereinafter DR) is based on the model of fully localized, inductively interacting bonds. Developed originally to predict the dipole moments of saturated molecules,[8] it was elaborated to yield bond energies [9] and made compatible with π-electron calculations in unsaturated molecules.[10,11] Its mathematical framework was investigated [12] and applications to large molecules came forward.[13] The advent of Extended Hückel [14] and other semiempirical all-valence-electron theories put DR somewhat in the shade, but interest in the nature of its results did not subside. A reappraisal and review of recent work are available.[15]

Although halogenated hydrocarbons have played a central role in the development of DR, it seems that systematic deviations of the calculated from measured dipole moments passed unnoticed. Inspection of columns A and B in Table 1 reveals shortcomings of two types: first, in molecules that contain non-geminal halogens, the calculated dipole moment is frequently too high; secondly, in molecules that contain geminal fluorines, the calculated dipole moment may be too low. It is easy to trace back the origin of these defects. In the non-geminal combination, mutual induction of the C–Hal bonds, a field effect [21] that acts to lower their electric moments,[22] is not accounted for. In the case of geminal fluorines, shortening of the C–F bond length [23] seems to have been overlooked. When realistic lengths (*i.e.*, short) are used in the calculation, dipole moments come out low. With other halogens bond contraction is less significant.

In what follows we propose ways to overcome these defects, and examine the outcome of incorporating DR electrostatics in the halide force field.

The Modified Del Re Scheme.—In DR,[8] the charge Q_M on atom M in a molecule is the sum of charges due to bonds in which M is involved, $Q_M = \Sigma Q_{\mu\nu}$ ($\mu\varepsilon$M and $\nu\varepsilon$N, where N is bonded to M). To each bond there corresponds a two-dimensional secular matrix and, in principle, $Q_{\mu\nu}$ can be evaluated from the characteristic

TABLE 1

Calculated [a] and experimental dipole moments (Debye [b])

Molecule	A μ(DR) [c]	B μ(exptl.) [d]	Deviation	C μ(MDR) [e]
1,2-Dichloroethane (*gauche*)	2.90	2.55 [f]	0.35	2.65
cis-1,2-Dichlorocyclohexane	3.37	3.12	0.25	3.09
cis-1,2-Dibromocyclohexane	3.34	3.12	0.22	3.07
trans-1,3-Dibromocyclohexane	2.30	2.19	0.11	2.17
cis-1,4-Dibromocyclohexane	2.96	2.89	0.07	2.81
Fluoroethane	1.88	1.94	−0.06	1.88
1,1-Difluoroethane	2.10	2.27	−0.17	2.29
1,1,1-Trifluoroethane [g]	1.97	2.31	−0.34	2.32

[a] Using the optimized geometries.[16–18] [b] 1 D $\sim$ 3.335 64 $\times$ 10^{-30} C m. [c] By Del Re's original formulation.[8] [d] Ref. 19. [e] By the Modified Del Re formulation (this work). [f] Temperature method. [g] Using the experimental geometry.[20]

vector. The diagonal element is written as $\delta_\mu - E$, where equation (1) applies. It is equation (1) that

$$\delta_\mu = \delta_\mu{}^0 + \sum_\nu \gamma_{\mu(\nu)}\delta_\nu \qquad (1)$$

limits the model to inductive effects: non-neighbouring atoms are made to influence each other only through the intervening bonds. The non-diagonal terms are denoted $\varepsilon_{\mu\nu}$. It turns out that $Q_{\mu\nu}$ can be approximated as (2).

$$Q_{\mu\nu} = (\delta_\mu - \delta_\nu)/2\varepsilon_{\mu\nu} \qquad (2)$$

To solve for the $Q_{\mu\nu}$ values one sets up the system of non-homogeneous linear equations in the δ_μs [equation (1)] and inserts the solving values in equations like (2).

One has thus to reckon with three types of constant: $\delta_\mu{}^0$ (atomic), $\gamma_{\mu(\nu)}$, and $\varepsilon_{\mu\nu}$ (bond). By fitting to experimental dipole moments, Del Re, and later Berthod [10,11] and others,[24] allotted numerical values to the parameters. Those values that concern the present investigation are listed in Table 2.

TABLE 2

DR Parameter values [a]

M	C	H	F	Cl	Br
δ_0(M)	0.07	0.00	0.57	0.35	0.33 [b]
M–N	C–C	C–H	C–F	C–Cl	C–Br
$\gamma_{\mu(\nu)}$	0.1	0.3	0.1	0.2	0.2 [b]
$\gamma_{\nu(\mu)}$	0.1	0.4	0.1	0.4	0.4 [b]
$\varepsilon_{\mu\nu}$	1.0	1.0	0.85 [c]	0.6 [b]	0.6 [b]

[a] From Ref. 8 except when noted otherwise. *Cf.* ref. 24. [b] Ref. 25. [c] Applicable in MDR only if F is not geminal to another F.

In dealing with geminal polyfluorination, we recognize that the nature of the C–F bond varies markedly in the series $-\overset{|}{\underset{|}{\mathrm{C}}}-\mathrm{F}$, $-\mathrm{CF_2}-$, $-\mathrm{CF_3}$. This is evident in the C–F bond length: 0.1382 in CH_3F, 0.1357 in CH_2F_2, and 0.1332 nm in CHF_3.[23] Also, by inserting the reported valence angles into the orthogonality constraints on hybridization indices,[26] one finds that the carbon bound to F is $sp^{3.49}$-hybridized in CH_3F, $sp^{3.18}$ in CH_2F_2, and $sp^{3.13}$ in CHF_3.[27] Therefore, not all the fluorine constants in Table 2 can apply to the groupings $-CF_2-$ and $-CF_3$. We chose to modify ε_{CF}, that is, compensate for the decrease in bond-length by increasing the bond-charge. By this choice, Del Re's original process of computation [equation (1)] is not affected, and rectification is deferred to the final position [equation (2)]. By fitting to experimental dipole moments, we settled on ε_{CF} 0.76 in $-CF_2$ (CH_3CHF_2,[19] 1,1-difluorocyclohexane [28]) and 0.67 in $-CF_3$ (CHF_3, CH_3CF_3).

Through-space interaction in polyhalides deserves a more fundamental treatment. To this end we define a 'pseudo-bond' X · · · X′ between non-geminal halogens X and X′, and attribute to it a γ-factor [required in equation (1)]. It is clear[29] that $\gamma_{XX'}$ should depend on the interatomic distance $R_{XX'}$. In his theoretical examination, Del Re concludes that the effect of atom N on atom M is related to the integral $I = \int(\chi_\mu{}^2/R_N)\mathrm{d}V$, where χ_μ is that atomic orbital on M that N perturbs [equation (10) of ref. 8]. A reasonable position would then be equation (3) where I conveys the dependence on

$$\gamma_{XX'} = \gamma^0{}_{XX'}I \qquad (3)$$

R. If χ_μ is approximated as a finite sphere centred on M, I is reciprocally proportional to R [8] [equation (4)].

$$I \sim \frac{1}{R} = I_1 \qquad (4)$$

In a first correction, χ_μ can be taken as a 1*s* atomic orbital, whereat [30] equation (5) is obtained. This shows

$$I \sim \frac{1}{R} - \left(1 + \frac{1}{R}\right)e^{-2R} = I_2 \qquad (5)$$

that I_1 is an upper bound to I.

For our needs it suffices to put $I = I_1$ in equation (3), that is, equation (6) holds, and compensate by excluding

$$\gamma_{XX'} = \gamma^0{}_{XX'}/R \qquad (6)$$

long pseudobonds (see below) and by a suitable choice of $\gamma^0{}_{XX'}$. We now use $\gamma^0{}_{XX'} = -0.02$ [for R in nm, equation (6)]. In addition to the MDR results in Table 1 (column C), the following dipole moments may be cited to illustrate the performance of equation (6): $BrCH_2CH_2Cl$ (gauche), calculated 2.59 D, measured 2.59 D; $BrCH_2CH_2Br$ (gauche), 2.53, 2.53; 1,3-dibromocyclohexane (*cis* diequatorial), 2.20, 2.17; 1,4-dichlorocyclohexane (*cis*), 2.82, 2.89 D.

We have calculated by now the dipole moments of *ca.* 80 structural species. The results in general are satisfying, but there are insufficiencies that call for further elaboration. Inclusion of the through-space X · · · X′ interaction counteracts the through-bond drift of charge from C to X in C–X, reducing thereby the negative charge computed at X. In a polyhalogenated molecule each halogen atom is involved in several X · · · X′ pseudobonds. If the interactions are taken as independent and additive, reductions accumulate and the bond charges become unacceptably low. Indeed, the effects of the various X′ on X cannot be superposable, since the resistance of X to further withdrawal of charge would increase as its net charge diminishes. Rather than build the variable resistance into the formulation [31] we circumvent the problem by truncation, that is, by ignoring X · · · X′ interactions when R exceeds a given threshold. This approach is dictated by the finding that $I \sim I_1$ [equation (4)] does not vanish quickly enough.

γ-1,2,3,4,5,6-Hexachlorocyclohexane (eeeaaa) is a case in point. Its dipole moment in benzene solution is 2.82 D.[32] With the original DR formulation (no pseudobonds) one calculates 3.81 D, too high; with all pseudobonds one gets 2.17 D, now too low. If pseudobonds longer than 0.52 nm are ignored (*i.e.*, 1,4-ae and 1,3-ee), the result is 2.83 D, in very good agreement with experiment. The same truncation (>0.52 nm) suits also the dipole moments of the α (eeeeaa) and δ (eeeeea) isomers.

Yet, the response of the computed charges to truncation is sometimes disturbing. Consider, and this is our worst example, the axial chlorine in the δ isomer. With all pseudobonds, its computed charge (−0.104 e) is still acceptable, but the molecular dipole moment comes out low (1.92 D *versus* the measured [32] 2.22); truncation at *R* 0.52 nm improves the dipole moment (2.06 D), but makes the charge unrealistically low (−0.003 e).

Another type of problem is encountered when one of the halogens is fluorine. Because of the relatively high δ_0(F), a F · · · Cl pseudobond (or F · · · Br) transfers too much charge from C–Cl (or C–Br) to C–F. As an example, one calculates for $ClCH_2CH_2F$ (*anti*) a dipole moment of 1.53 D (certainly too high), *versus* 0.13 D (reasonable [17]) when the F · · · Cl interaction is ignored. An exaggerated redistribution results also when a molecule contains fluorines of different types, as in CF_3CHF_2. A way out in the first case is to ignore the pseudobond, and in the second to use an average value for ε_{CF}. We do not know as yet how general such procedures are.

In brief, the shortcomings of DR are not all overcome, but one can check by inspection whether the computed charges in a given case are within range and suitable for the force-field stage.

Force field.—The force field we propose is an offshoot of the dipole force field.[16-18] The main difference is that the intramolecular electrostatic interaction is now expressed as in equation (7) where the summation is over

$$E_{es} = \Sigma Q_i Q_j / R_{ij} \qquad (7)$$

all pairs of atoms that are not bound to each other nor to a common atom. Note that the 'intramolecular dielectric constant' *D*, which would divide the expression of E_{es} (*i.e.*, $E_{es} = \Sigma Q_i Q_j / D R_{ij}$) is here taken as unity. This is not an obvious choice,[3,33,34] but it is a reasonable first try. Since *D* was put equal to 4 in the dipole version of the force field,[16-18] E_{es} is now higher than before, and some of the previously employed torsional constants have to be replaced. To recapitulate, the torsional energy is written as a sum, $E_{tor} = \Sigma e_{tor}$, where each e_{tor} depends on the dihedral angle ω in a four-atom sequence, $e_{tor} = \frac{1}{2}[V_1(1 + \cos\omega) + V_2(1 - \cos 2\omega) + V_3(1 + \cos 3\omega)]$.

TABLE 3

Changed torsional constants [a] (kJ mol^{-1})

	V_1	V_2	V_3
H–C–C–F	1.883	0	1.632
H–C–C–F(g)	1.255	0	1.046
H–C–C–Cl	1.464	0	1.799
C–C–C–F(g)	−0.795	0	1.966
C–C–C–Br	0	−1.674	0
F–C–C–F(g)	0	0.711	0
Cl–C–C–Cl [b]	−5.439	6.527	−4.561
Br–C–C–Br	−3.012	3.264	5.607

[a] Constants for F in $-CF_2-$ are labelled (g). [b] The set (0, 1.506, 0.251) performs better in most cases, but it overestimates the rotational barrier in $ClCH_2CH_2Cl$.

Modified torsional constants are listed in Table 3. All other force field parameters (stretching, bending, *etc*., and the unlisted torsional constants) are as before.[16-18]

In updating the constants, vicinal difluorides were not considered, since even the data for FCH_2CH_2F are controversial.[35,36] The constants listed for F–C–C–F(g) are based on fitting to one sole compound, F_2CHCHF_2, but here the F–C–C–F strain comes out low and of almost no effect on ΔE_t. Indeed, MDR charges account by themselves for the *gauche-anti* energy difference in F_2CHCHF_2: the computed ΔE_{es}(g − a) is 5.035 kJ mol^{-1} and all other contributions add up only to −0.166, so that ΔE_t = 4.87 kJ mol^{-1}; the experimental value [37] is *ca*. 4.89 kJ mol^{-1}. This result confirms [38] the electrostatic origin of the conformational energy in F_2CHCHF_2. Quantum chemical criteria [39,40] (bonding–antibonding interactions) suggest that *gauche* is the more stable conformer, contrary to experimental evidence.

The F–C–C–F(g) constants were used to calculate the conformational energy in $CH_3CF_2CF_2CH_3$. Here ΔE_t(g − a) comes out as 8.10 kJ mol^{-1}, of which 4.26 is of electrostatic origin; the rest is mostly made up of torsional and bending strain. Whatever the criteria [39,40] predict, an actual *ab initio* calculation [41] does identify *gauche* as the less stable conformer. The energy difference in *ab initio* depends heavily on the geometry and the basis set, but the preferred estimate is *ca*. 5.77 kJ mol^{-1}.[41] Our optimized value for the C–C–C–C angle in *gauche* is 64°, perhaps more plausible than the quantum chemical estimate, 82°.

DISCUSSION

Since most of the molecules calculated had been previously studied by force-field methods, only an overview and a discussion of some pending problems will be given here. Calculated ΔE_t values may be considered 'very satisfactory' when within 0.4 kJ mol^{-1} of the experimental (that is, *ca*. 0.1 kcal mol^{-1}), and 'fairly good' when within 2 kJ mol^{-1} (*ca*. 0.5 kcal mol^{-1}).

TABLE 4

Component analysis for four molecules (kJ mol^{-1})

	$C_6H_{11}Br$ [a]	C_5H_9Br [a]	C_3H_7Br [b]	$C_6H_{10}Cl_2$ [c]
stretch (ΔE_s)	0.094	0.008	0.034	0.292
bend (ΔE_b)	1.880	−0.309	1.128	1.202
nonbonded (ΔE_{nb})	0.801	−0.671	0.285	1.405
torsion (ΔE_{tor})	−2.268	−2.743	−0.906	−2.984
charge (ΔE_{es})	1.514	1.059	0.771	−2.528
Total (ΔE_t)	2.02	−2.66	1.31	−2.61
Experimental	~2.03 [d]	~−2.51 [e]	~−0.42 [f]	~−2.93 [g]

[a] *E*(axial) − *E*(equatorial). [b] *E*(*gauche*) − *E*(*anti*). [c] 1,2-*trans*-Dichlorocyclohexane, *E*(diaxial) − *E*(diequatorial). [d] Ref. 42. [e] Refs. 43 and 44. [f] Ref. 45. [g] Ref. 46.

Consider the component analyses in Table 4. In bromocyclohexane and bromocyclopentane (envelope, prow-halogen), the most stable conformers are, respectively, equatorial and axial. By calculation, 1-bromopropane mimics bromocyclohexane (*anti* is the acyclic analogue of the equatorial orientation), contrary to observation: available data indicate that halogenopropanes all prefer the *gauche*-conformation.[3] *trans*-1,2-Dichlorocyclohexane is included in Table 4 because the dipole field,[16] unlike the present MDR field, overestimated the stabilization of the diaxial form. The fault there was with the Cl–C–C–Cl torsional constants which, in turn, were assigned so as to comply with the dipole electrostatics of $ClCH_2CH_2Cl$.

There are several things to note in Table 4. First, the difference in electrostatic energy (ΔE_{es}) may or may not be representative of the total difference in energy (ΔE_t). This must also be true of other force fields. Therefore, it is unsafe to assume *a priori* that $\Delta E_t \sim \Delta E_{es}$,[47] nor to assess the quality of a computed charge distribution by comparing the corresponding ΔE_{es} with the experimental ΔE.[48]

Second, the torsional term (ΔE_{tor}) is not necessarily small, so that an appreciable fraction of ΔE_t may remain 'unexplained'.[3] Yet, it is not the 'unexplained' strain, nor the intramolecular electrostatics,[44] that account for the opposing tendencies in $C_6H_{11}Br$ and C_5H_9Br. Calculation points mainly at bending strains: E_b is higher in axial $C_6H_{11}Br$ than in the equatorial, but the two conformers of envelope C_5H_9Br have comparable E_b values. This is to be stressed since, in interpreting stereochemical propensities, one tends to concentrate on nonbonded interactions.[49] Note that nonbonded repulsions actually favour the 'wrong' conformer of 1,2-*trans*-dichlorocyclohexane. The conformational bias in this case is interpreted as partly due to charge interaction, and partly 'unexplained'.

The difficulty to fit a force field simultaneously to halogenocyclohexanes and 1-halogenopropanes, or even both to 1-halogenopropane and to its derivatives, is well documented.[3,16-18,50] A force field [38] developed to reproduce the measured conformational energy in $CH_3CH_2CH_2X$ ($X = F$, Cl) was less successful with $XCH_2CH_2CH_2X$ and even less for XCH_2CHXCH_2X. By another field,[51] adapted this time to halogenocyclohexanes ($X = F$, Cl, Br), the *anti*-conformation of 1-halogenopropanes was calculated to be more stable than the *gauche*.[52] In a calculation of bromides by a field fitted to bromocyclohexane, the inevitable discrepancy in the case of 1-bromopropane carried sometimes over to more complex bromoalkanes and sometimes did not.[18] The problem is particularly conspicuous in a study of halides [50] where, depending on the halogen, ΔE_t has the desired sign either in the cyclic or in the acyclic case, but not in both. This incompatibility cannot be a consequence of the habitual disregard for molecular vibration [53,54] (in passing from the theoretical ΔE_t to populations), since this factor is frequently ignored also in processing the experimental data (in passing from the measured populations to ΔE). It is interesting to note that quantum chemical calculations also make *anti* more stable than *gauche*.[55] Note that the experimental data on halogenopropanes are not recent. Re-examination of these small conformational energies would be of much help.

The present field was adjusted, by appropriate choice of the C–C–C–X torsional constants, to fit halogenocyclohexanes. Optimized geometries were then scanned for details that might distinguish 'ill behaved' from 'well behaved' cases. As illustrated in Table 5, we find that the nonbonded $C^1 \cdots X^4$ distance is relatively long in the *anti*-conformation of 'ill behaved' halogenopropanes, and relatively short in the *gauche*. It could be, then, that our function overestimates the $C \cdots X$ 1,4-repulsion at the shorter distances (acyclic *gauche*) and the 1,4-attraction at the longer (acyclic *anti*). Since the problem is common to force fields of variegated forms, reparametrization is not expected to provide a ready remedy. One had better wait for a pertinent theoretical model, perhaps having to do with the distortion of orbitals under the effects of proximity,[56] and only later attempt to recast the evolving picture in molecular mechanical terms.

TABLE 5

Calculated 1,4-nonbonded $Br \cdots C$ distances (nm)

Structure [a]	Distance in eq or a	Distance in ax or g
$C_6H_{11}Br$, eq or ax	0.4289	0.3445
C_5H_9Br, eq or ax	0.4184	0.3443
$C_6H_{10}Br_2$,[b] ee or aa	0.4289	0.3440
$CH_3CH_2CH_2Br$, a or g	0.4291	0.3427
$BrCH_2CH_2CH_2Br$ [c]		
AA or GG	0.4285	0.3441
AG	0.4299	0.3428
$BrCH_2CHBrCH_2Br$ [c]		
AA(gg) or GG(ga)	0.4294	0.3405
GA(gg)	0.4293	0.3328
GA(ag)	0.4305	0.3429

[a] Eq, ax, ee, aa, a, g = equatorial, axial, diequatorial, diaxial, *anti*, *gauche*, respectively. [b] 1,4-*trans*-Dibromocyclohexane. [c] Capital and small letters refer, respectively, to the conformation of the BrCCC or BrCCBr fragment.

In anticipation, consider the effect of an *ad hoc* correction. In C_3H_7Br, the calculated ΔE_t is off by δ *ca.* 1.73 kJ mol^{-1} (calc. +1.31, exp. −0.42; see Table 4); in the fluoro- and chloro-analogues, δ *ca.* 0.84 and 1.67, respectively. By subtracting δ from ΔE_t for each acyclic *gauche*-interaction, one gets a 'corrected' energy, $E_{t,cor}$. Some examples are collected in Table 6. Results by another recent force field,[38] wherein the nonbonded function was adapted to acyclic halogenoalkanes, are cited for comparison.

It is clear from Table 6 that the present results (ΔE_t) improve upon earlier fields,[17,18,59,61] and that the *ad hoc* rectification ($\Delta E_{t,cor}$) reflects a systematic trend. It is also clear, however, that the correction does not apply equally well to all types of compound. It fits fairly the last two entries, where the non-troublesome XCCX strains outweigh interactions across the XCCC sequence; but it performs only poorly in the first three molecules, even though they are closer in structure to the parent halogenopropane. The problem, then, must be of a fundamental origin.

As a further check on the electrostatics and $\Delta E_{t,cor}$, we used Mizushima's equation [62] to calculate the conformer population in $BrCH_2CHBrCH_2Br$ at 25 °C, for a medium of ε *ca.* 2. The results, in the tabulated order of species, are: 68, 27, 4.1, and 6.9%; experimental estimates [63] are 70% GG(ga) in DMSO and 84% in CCl_4. Using the calculated dipole moments (Table 6, note *g*), one obtains an average of 1.47 D. The experimental counterpart,[64] in heptane at 25 °C, is 1.51 ± 0.02 D.

TABLE 6

Conformational energies in polyhalogenated propanes (kJ mol^{-1})

Molecule and conformation [a]	ΔE_{es}	ΔE_t	$\Delta E_{t,cor}$	ΔE(exp.)	Previous work [b]
$FCH_2CH_2CH_2F$					
GG	0	0	0	0 [c]	0
AG	0.248	1.115	1.96	2.09—4.73	6.57
AA	2.991	4.714	6.39	5.02	13.72
GG′	9.378	9.808	9.81	1.67	6.07
$ClCH_2CH_2CH_2Cl$					
GG	0	0	0	0 [d]	0
AG	0.467	0.102	1.77	4.60	5.44
AA	1.768	1.474	4.81	$\geqslant$6.28	9.37
GG′	5.673	9.875	9.88	~10.04	
$BrCH_2CH_2CH_2Br$					
GG	0	0	0	0 [e]	
AG	0.600	0.100	1.63	~4.18	
AA	1.615	0.490	3.95	~6.69	
GG′	4.730	10.476	10.48		
$ClCH_2CHClCH_2Cl$					
GG(ga)	0	0	0	0 [f]	0
GA(ag)	0.580	0.384	2.05	2.09—3.77	6.36
GA(gg)	5.086	4.726	6.40	>4.60	10.54
AA(gg)	6.511	6.035	9.37		16.02
$BrCH_2CHBrCH_2Br$ [g]					
GG(ga)	0	0	0	0 [h]	
GA(ag)	0.355	0.685	2.42	4.60—7.95	
GA(gg)	3.314	5.835	7.56	4.60—7.95	
AA(gg)	4.776	6.940	10.40		

[a] Capital and small letters denote, respectively, conformation in the XCCC and XCCX fragments; G or g = *gauche*, A or a = *anti*. [b] Ref. 38. [c] Ref. 57, see also ref. 17. [d] Ref. 58. [e] Ref. 53, see also refs. 18 and 59. [f] Ref. 60. [g] The calculated dipole moments, in the given order of conformation, are 1.35, 1.50, 2.51, and 2.75 D. [h] Ref. 61, where calculations by an early force field are also reported.

To round up, consider one of Stolow's test-cases:[48] in 4-chloro-1,1-difluorocyclohexane the axial conformation is the more stable, despite its being a derivative of chlorocyclohexane. By MDR (modified fluorine parameters, no pseudobonds), C^1 is positive (+0.417 e) and C^2 negative (−0.045 e), in contrast with the Smith–Eyring distribution[6] which makes both carbons positive.[48] We can thus interpret the stereochemical bias as due mainly to a larger electrostatic $Cl \cdots C^1$ attraction in the axial form ($|\Delta e_{es}|$ 4.26 kJ mol^{-1}); this gain is attenuated, *inter alia*, by the lower $Cl \cdots C^2$ and $Cl \cdots C^6$ repulsions ($|\Delta e_{es}|$ 0.71 each). Overall, one gets $\Delta E_{es}(eq - ax) = 2.71$ kJ mol^{-1}. As in the halogenocyclohexanes, steric strains favour the equatorial form, $\Delta E_{st}(eq - ax)$ −0.569, with the consequence that the sign of ΔE_t, although not its magnitude,[4] is determined by electrostatic features. For comparison, the corresponding numbers for chlorocyclohexane are $\Delta E_{es}(eq - ax)$ −1.707, ΔE_{st} −0.084, and ΔE_t −1.79 kJ mol^{-1}.

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