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Adjacent Gauche Stabilization in Linear Alkanes: Implications for Polymer Models and Conformational Analysis

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Abstract

High-level *ab initio* quantum mechanical calculations are used to study various gauche conformational energies of n-pentane to n-decane. The destabilizing “pentane effect” (adjacent gauche states of opposite sign) for alkanes is confirmed, but the energies were found to depend slightly on chain length. In contrast, introducing an adjacent gauche of the same sign requires only 0.22–0.37 kcal/mol, approximately half of the single gauche state energy. This adjacent gauche stabilization should be taken into account when formulating or analyzing rotational isomeric models, carrying out conformational analysis, and developing force fields for alkanes, lipids, and related polymers.

The modeling of intra- and intermolecular interactions of alkanes is not only important for hydrocarbon research but also for polymers and biological compounds such as lipids. For polymer research, the rotational isomeric state (RIS) model was developed by Flory in 1969.¹ The fundamental parameter of the RIS model is ΔE_g , the energy difference between the trans (*t*) and gauche (*g*); this is 0.5 kcal/mol for alkanes. This energy is assumed to be additive for all gauche states other than g^+g^- pairs, which have a substantially higher energy than $2 \times \Delta E_g$; this destabilization is called the “pentane effect” and is primarily steric in origin.^{1,2} Organic chemists more commonly refer to the effect as “syn-pentane interaction”, and recognize its importance in conformational analysis.³

High-level *ab initio* quantum mechanical (QM) calculations on pentane through heptane yields a ΔE_g slightly higher than 0.5 kcal/mol,^{4–6} while $\Delta E_{g^+g^+}$ is lower than $2 \times \Delta E_g$. Atomic force fields, such as CHARMM27 (C27),^{7,8} agree with the QM calculations, and indicate that long-range attractions in the g^+g^+ (equivalently, g^-g^-) states stabilize adjacent gauche conformations.⁶ Klauda et al.⁶ termed this stabilization the “positive pentane effect” (to contrast the destabilizing pentane effect). In this letter, a more extensive set of calculations is reported to further characterize the effect and to help determine its implications for polymer and lipid modeling. We have renamed this behavior “adjacent gauche stabilization” (AGS) for increased clarity.

Pentane was used as a test case to determine the optimal QM theory and basis set for optimizations and conformational energy calculations. The Gaussian03 suite of programs⁹ was used for all QM calculations. Conformational minima were optimized using tight convergence criteria (1.5×10^{-4} and 1.0×10^{-4} hartree/bohr for maximum and RMS force) and a starting structure near the corresponding geometry.

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Previously it was found that geometry optimizations with MP2/cc-pVDZ were superior to those with density functional theory.⁶ The effect of basis set was minimal, but higher level QM and g^+g^+ and g^+g^- conformations were not tested. Consequently, we performed optimizations at that compared results at CCSD/cc-pVDZ and MP2/cc-pVDZ for the tt , tg , g^+g^+ , and g^+g^- conformations of pentane. The carbon-carbon bond lengths were nearly identical for CCSD and MP2 and only a slight increase was obtained in the carbon angles (approximately 0.3°) for the higher level calculation. The minima for g^- , t , and g^+ states are close to -60° , 180° and 60° , respectively, and are usually independent of the values of neighboring dihedrals. The exception is g^+g^- , where $g^+ \cong 60^\circ$, $g^- \cong -90^\circ$. There was negligible difference for the t state dihedrals and on average only a 0.6° deviation for the g dihedrals.

These slight variations in geometry are only important to our work if they effect the relative energy of conformation i with respect to the all trans state, ΔE_i . For these energy calculations, CCSD(T) is required to reduce the underestimate of the MP2 g^+ minima.⁶ This is evident in Table 1, where the largest deviations between MP2 and CCSD(T) occurs for the adjacent gauche states, and MP2 overestimates the AGS by 14%.

The differences for the conformational energies with geometries optimized at MP2/cc-pVDZ and CCSD/cc-pVDZ are small, less than 0.02 kcal/mol. The slight deviations in geometries have a negligible effect on ΔE_i . Therefore, all conformational geometries are optimized with MP2/cc-pVDZ.

The CCSD(T) results in Table 1 provide strong support for AGS in pentane. Since CCSD(T) calculations with basis sets larger than cc-pVTZ are intractable even for a small alkane like pentane, an alternate approach is required to obtain an estimate of the CCSD(T) energy with a large basis set (LBS). One such method assumes that the differences in energies for the large and small basis sets (SBS) are the same for MP2 and CCSD(T),¹⁰⁻¹³ and CCSD(T)/LBS energy is estimated as follows

$$E[\text{CCSD(T) / LBS}] \cong E[\text{CCSD(T) / SBS}] + (E[\text{MP2 / LBS}] - E[\text{MP2 / SBS}]) \quad (1)$$

Klauda et al.¹⁰ determined that the differences between energies using eq 1 with a LBS of cc-pVQZ and cc-pV5Z were negligible and near the basis set limit (SBS=cc-pVDZ). In addition, the approximate CCSD(T)/cc-pVQZ energy differences for butane using eq 1 are accurate within about 1–2% from the CCSD(T) energy differences with a nearly complete basis set.⁶ The errors in the conformational energies associated with an incomplete basis set and optimization at a lower level of theory are at most ± 0.04 kcal/mol. Therefore, all energies reported in subsequent tables use eq 1 with SBS=cc-pVDZ and LBS=cc-pVQZ and are denoted MP2:CC.¹⁰

The conformational energies of single and adjacent g^+ states for normal alkanes from butane to decane are listed in Table 2. On the diagonal of Table 2 are the all g^+ conformations for each alkane. For the other conformations, there is one trans state at the beginning of the chain and then m g^+ dihedrals with the remaining carbon dihedrals as trans.

As evident from Table 2, there is a strong chain length dependence of ΔE_i for the shorter alkanes, i.e., a 14% reduction in the gauche energy from butane to octane. However, the dependence of ΔE_g on the chain length becomes negligible for alkanes larger than octane. There is a 19–20% reduction for states with two and three adjacent g^+ states. Long-range intramolecular dispersion stabilizes these gauche states.¹⁰

The significant stabilization that occurs for conformations with adjacent gauche states is the focus of this work. In RIS models ΔE_g is independent of its neighboring torsional state, but clearly from Table 2 this assumption is incorrect. Once a chain is “seeded” with a single gauche

state at the cost of 0.54–0.62 kcal/mole, the energy of adding an adjacent gauche of the same sign is only 0.22–0.37 kcal/mol.

The stabilization effect is negligible for alkane conformations with g^+ states that are separated by a dihedral, especially for larger alkanes. This was tested for $tg^+tg^+t_{n-7}$ conformations of hexane to decane. For hexane the effective ΔE_g per gauche state, $\langle \Delta E_g \rangle$, is 0.59 kcal/mol with a slight stabilization compared to ΔE_{tgt} , but the $\langle \Delta E_g \rangle$ for the staggered gauche state of decane is identical to that in Table 2 (0.54 kcal/mol).

The final set of QM calculations listed in Table 3 is for adjacent gauche conformations with a single g^- state at the end, $t(g^+)mg^-t_{n-m-5}$ where n is the number of carbons in the alkane and m is the number of g^+ states. As with the pure g^+ configurations, there is moderate chain length stabilization for the configurations in Table 3, e.g., 13% reduction in $\Delta E_{g^+g^-}$ from pentane to nonane. However, the $\Delta E_{tg^+g^-t_{n-5}}$ appears to reach an asymptote for alkanes larger than nine carbons.

The QM results indicate that an additional adjacent gauche state correction term is required for the RIS model. The total energy of an alkane or saturated polymer can be modeled as,

$$E(\text{total}) = n_g \Delta E_g + n_{g^+g^-} \text{AGD} + n_{g^+g^+} \text{AGS} \quad (2)$$

where the number of gauche and pairs of g^+g^- and g^+g^+ in a chain are n_g , $n_{g^+g^-}$ and $n_{g^+g^+}$, respectively. The adjacent gauche destabilization (AGD) or “pentane effect” is the additional energy required for a single adjacent g^- state. The new term, AGS, in eq 2 is the stabilization energy for each g^+g^+ pair in a chain. In the RIS model by Flory,¹ the ΔE_g effectively includes AGS and, consequently, ΔE_g is slightly smaller than the values in Table 2.

The RIS model also assumes that the curvature for each conformational minimum is equal, so that the statistical weights are equal for all minima. The MP2:CC curvature of the $tttt$, $tggt$ and tg^+g^+t minima of heptane is 1.9×10^{-3} , 3.2×10^{-3} and 4.0×10^{-3} kcal/(mol deg²), respectively.⁶ The curvature increase for each gauche state is about 1×10^{-3} kcal/(mol deg²), which suggests that further refinements of the RIS model should include different statistical weights.

The terms in eq 2 are shown in Figure 1 as a function of the hydrocarbon chain length. The value for AGS for each alkane of length n was obtained from eq 2 with the corresponding energies in Table 2 using root mean squared (RMS) fits to all g^+g^+ conformations. AGD was obtained similarly from Table 3. There is only a small chain length dependence on the AGS and ADG energies (3.4% reduction from pentane to decane). The average AGS and AGD over all alkanes is -0.26 and $+1.56$ kcal/mol, respectively.

Atomic force fields used in molecular simulation partially include AGS with the attractive intramolecule long-range dispersion via the 6–12 Lennard-Jones (LJ) potential. However, these LJ parameters are typically fit to reproduce intermolecular interactions and phase behavior. AGS is not consistently taken into account in force fields such as C27 and C27r (revised C27 to best fit a subset of alkane QM calculations presented here).⁶ For example, C27r calculated ΔE_i for decane with tg^+t_5 , $t(g^+)_2t_4$, $t(g^+)_3t_3$ and $(g^+)_7$ conformations deviate from MP2:CC by 0.02, 0.14, 0.31 and 0.99 kcal/mol, respectively.

In conclusion, the assumption that ΔE_g is independent of neighboring dihedrals in the RIS model is invalid. This is evident in Figure 1 and Table 2 where significant stabilization exists for adjacent gauche states of the same sign. The energies of gauche states depend on the chain length for small alkanes, though the AGS is relatively independent of chain length. Force fields

should reproduce energies presented here, especially AGS, to obtain accurate populations of conformational states in polymers and lipids.

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Figure 1.
Terms for eq 2 (RIS-like model) obtained from MP2:CC energies.

Table 1

The ΔE_i in kcal/mol (single point energy//optimization) for pentane with DZ=cc-pVDZ and TZ=cc-pVTZ.

Conf.	MP2/TZ //MP2/DZ	CCSD(T)/TZ //MP2/DZ	%Error MP2	CCSD(T)/TZ //CCSD/ DZ
tg	0.56	0.59	+5.1	0.59
g^+g^+	0.80	0.93	+14.0	0.95
g^-g^-	2.81	2.78	-1.1	2.79

Table 2

The MP2:CC ΔE_i energy in kcal/mol, where $(g^+)_m$ for the first alkane in a column and $t(g^+)_{m}t_{n-m-4}$ for n alkane carbons.

Alkane	$m=1$	2	3	4	5	6	7
$n=4$	0.63						
5	0.62	0.99					
6	0.60	0.93	1.27				
7	0.56	0.87	1.19	1.54			
8	0.54	0.82	1.09	1.45	1.81		
9	0.54	0.80	1.04	1.36	1.72	2.06	
10	0.54	0.80	1.02	1.31	1.62	1.97	2.32

Table 3

The MP2:CC ΔE_i energy in kcal/mol, where $i=(g^+)_{mg^-}$ for first alkane in the column and $t(g^+)_{mg^-}t_{n-m-5}$ for n alkane carbons.

Alkane	$m=1$	2	3	4	5	6
$n=5$	2.85					
6	2.74	3.12				
7	2.54	2.95	3.48			
8	2.51	2.70	3.39	3.74		
9	2.49	2.61	3.17	3.65	3.99	
10	2.49	2.59	3.11	3.43	3.90	4.24