Performance of Ab Initio and Density Functional Methods for Conformational Equilibria of C_nH_{2n+2} Alkane Isomers ($n = 4-8$)[†]

David Gruzman, Amir Karton, and Jan M. L. Martin*

Department of Organic Chemistry, Weizmann Institute of Science, IL-76100 Rechovot, Israel

Received: April 21, 2009; Revised Manuscript Received: July 13, 2009

Conformational energies of *n*-butane, *n*-pentane, and *n*-hexane have been calculated at the CCSD(T) level and at or near the basis set limit. Post-CCSD(T) contributions were considered and found to be unimportant. The data thus obtained were used to assess the performance of a variety of density functional methods. Double-hybrid functionals like B2GP-PLYP and B2K-PLYP, especially with a small Grimme-type empirical dispersion correction, are capable of rendering conformational energies of CCSD(T) quality. These were used as a "secondary standard" for a larger sample of alkanes, including isopentane and the branched hexanes as well as key isomers of heptane and octane. Popular DFT functionals like B3LYP, B3PW91, BLYP, PBE, and PBE0 tend to overestimate conformer energies without dispersion correction, while the M06 family severely underestimates GG interaction energies. Grimme-type dispersion corrections for these overcorrect and lead to qualitatively wrong conformer orderings. All of these functionals also exhibit deficiencies in the conformer geometries, particularly the backbone torsion angles. The PW6B95 and, to a lesser extent, BMK functionals are relatively free of these deficiencies. Performance of these methods is further investigated to derive conformer ensemble corrections to the enthalpy function, $H_{298} - H_0$, and the Gibbs energy function, gef(T) $\equiv -[G(T) - H_0]/T$, of these alkanes. These are essential for accurate computed heats of formation of especially the larger species as the corrections for these are several times the expected uncertainty in modern computational thermochemistry methods such as W4 theory. While $H_{298} - H_0$ is only moderately sensitive to the level of theory, gef(T) exhibits more pronounced sensitivity. Once again, double hybrids acquit themselves very well. The effects of zero-point energy and nonfactorizable rovibrational partition functions have been considered.

I. Introduction

The existence of multiple conformers for *n*-butane and higher *n*-alkanes has been known since the pioneering work of Pitzer.[1] (See the introductions to refs 2−4 for a detailed bibliography.) The importance of alkanes, in particular, as basic building blocks of organic chemistry and as constituents of fossil fuels requires no further elaboration nor indeed does that of aliphatic chains, in general, as moieties of lipids, of polymers like polyethylene, or of nanosystems.

Modern high-accuracy theoretical thermochemistry methods, such as W4 theory developed at Weizmann[5,6] and HEAT developed by a multinational consortium of researchers,[7−9] are capable of calculating bottom-of-the-well total atomization energies (TAE$_e$ values) with 95% confidence intervals of 1 kJ/mol (0.24 kcal/mol) or less. For alkanes and other systems devoid of low-lying excited electronic states, the chief factors limiting the accuracy of calculated total atomization energies (TAE$_0$) or heats of formation ($\Delta H^\circ_{f,0}$) at absolute zero are actually not of an electronic structure nature so much as the zero-point vibrational energies (ZPVEs), particularly the anharmonic corrections in them. At finite temperatures, this is compounded by the necessity of reliable heat content functions or enthalpy functions ($H_{298} - H_0$). By way of illustration, a component breakdown of heat content functions for a number of lower alkanes is presented in Table 1. For *n*-octane, the conformer contribution is seen to reach 1.08 kcal/mol. Clearly, when working in the kJ/mol accuracy region, one neglects such contributions at one's peril.

Smith and Jaffe[2] studied the conformational energies of *n*-butane and the central torsion of *n*-hexane in considerable detail. For *n*-butane, they obtained a trans−gauche energy of 0.59 kcal/mol at the CCSD(T)/cc-pVTZ//MP2/6-311G(2df,p) level. After correction, this was within 0.05 kcal/mol of the then-latest experimental value by Herrebout et al.[10]

Allinger et al.[3] carried out a "focal point"[11,12] convergence study on the butane conformer energies and torsional barriers. Their best estimate for the trans−gauche energy was 0.62 kcal/mol, just 0.04 kcal/mol lower than the very recent measurement by Balabin,[13] 0.660 ± 0.022 kcal/mol.

A similar focal point study for *n*-pentane was published by Salam and Deleuze[4] in 2002. Their best estimates for the relative energies of the TG (trans−gauche), GG (gauche$^+$ −gauche$^+$), and GX$^-$ (gauche$^+$−perpendicular$^-$) conformers are 0.621, 1.065, and 2.917 kcal/mol, respectively. Very recently, the TG and GG conformer energies were measured by Balabin[13] to be 0.618 ± 0.006 and 0.940 ± 0.020 kcal/mol, respectively. Note that the GG conformer is about 0.3 kcal/mol more stable than what one would expect from naively adding two TG energies; the GG conformer benefits from a mild dispersive stabilization (see, e.g., refs 13 and 14).

Tasi et al.,[15] in their paper on the enumeration of conformers in *n*-alkanes, discuss *n*-pentane at some length. Figure 1 in their paper is an energy landscape of *n*-pentane in terms of the two CCCC torsion angles. (In the remainder of this paper, we will adopt their notation for conformers, g ± for gauche torsion angles around ±60°, x± for "cross" or "perpendicular" angles around

---

[†] Part of the "Walter Thiel Festschrift".

* To whom correspondence should be addressed. E-mail: gershom@weizmann.ac.il.

10.1021/jp903640h CCC: $40.75

TABLE 1: Component Breakdown of the Theoretical Enthalpy Functions $H_{298} - H_0$ (kcal/mol) of Several Lower Alkanes and Comparison between Theoretical and Experimental Values[a]

				$H_{298} - H_0$	
				this work	expt.
	vibrational[b]	conformer[c]	internal rotation[b]	total	CCCBDB[d]
ethane	0.41	0.00	0.05	2.83	2.84
propane	1.08	0.00	0.09	3.54	3.52
n-butane	1.86	0.26	0.13	4.62	4.61
n-pentane	2.68	0.47	0.19	5.7	5.78
n-hexane	3.51	0.68	0.24	6.79	6.86
n-heptane	4.35	0.89	0.28	7.87	7.94[e]
n-octane	5.20	1.08	0.35	8.97	9.03[e]
isobutane	1.81	0	0.11	4.29	4.29
isopentane	2.65	0.09	0.19	5.3	5.26
neopentane	2.41	0	0.06	4.84	5.54[f]
isohexane	3.45	0.24	0.21	6.28	6.29
3-methylpentane	3.50	0.26	0.24	6.37	6.23
diisopropyl	3.44	0.04	0.22	6.07	5.85
neohexane	3.41	0	0.20	5.98	6.01
isoheptane	4.34	0.46	0.29	7.44	7.39[e]
neoheptane	4.28	0.15	0.21	7.01	6.98[e]
hexamethylethane	4.92	0	0.22	7.52	7.53[e]
isooctane	5.02	0.16	0.22	7.77	7.69[e]

[a] At room temperature, $[H_{298} - H_0]_{\text{trans+rot}} = 4RT = 2.37$ kcal/mol for all practical intents and purposes. [b] Reference 41. [c] Present work; the values here may differ by 0.01−0.03 kcal/mol from the values given in the Supporting Information of ref 41 due to the use of a slightly different s_6 value for the B2K-PLYP-D functional (see text). [d] NIST CCCBDB[49] unless indicated otherwise. Most of these data are taken from the next reference. [e] Scott, D. W. Chemical Thermodynamic Properties of Hydrocarbons and related substances, U.S. Bureau of Mines Bulletin No. 666; US Government Printing Office: Washington, DC, 1974. Available online at http://digicoll.manoa.hawaii.edu/techreports/PDF/USBM-666.pdf. Indirectly (via TRC database), the source for most of the CCCBDB data. [f] As shown in ref 41, this value is erroneous.

±90°, and t for trans.) It is seen there (as well as in the lower part of Figure 1 in the present paper) that the landscape has 11 minima, the global tt minimum, two equivalent gg minima (g^+g^+ and g^-g^-), four equivalent tg minima (t^+g^+, t^+g^-, g^+t, and g^-t), and finally four equivalent gx^- minima (g^+x^-, g^-x^+, x^+g^-, and g^-g^+). The gx^- conformer is often, confusingly, labeled g^+g^- in older literature; in fact, the actual g^+g^- structure is a transition state for a shallow barrier between equivalent g^+x^- and x^+g^- structures (and similarly for g^-g^+ between x^-g^+ and g^-x^+).

Because of this latter phenomenon (first pointed out, to the best of our knowledge, by Osawa and co-workers[14]), higher *n*-alkanes have more conformers than would be expected by naive "3^n" enumeration based on trans/gauche$^+$/gauche$^-$ products. This latter approach does lead to the correct four conformers for *n*-pentane (even as it mislabels the energetically highest one) but only yields 10 unique conformers on the *n*-hexane surface while in reality there are 12. A graphical representation of the conformer space of *n*-hexane can be seen in the upper part of Figure 1.

While the ttt, gtt, tgt, tgg, gtg, gtg^-, and ggg conformers also occur in the naive 3^n enumeration and the naive gg^-g conformer can be regarded as a "rounded-off" equivalent of the actual xg^-x conformer, the naive ggg^- and gg^-t conformers actually each correspond to nonequivalent pairs, gx^-t/xg^-t and gx^-g/ggx^-, respectively.

Tasi et al.[15,16] defined rules for a more correct conformer enumeration based on pruning a 5^n search down by excluding "forbidden" sequences that exhibit excessive sterical hindrance. The rules can be summarized as follows:

- The g^+g^-, g^-g^+, x^+x^-, and x^-x^+ sequences are forbidden. Instead, g^+x^-/x^+g^- and g^-x^+/x^-g^+ pairs occur.
- The gx^-g, xgx^-, and their isomorphs are forbidden.
- The xg^-g^-x sequence and its isomorph x^-ggx^- are forbidden.

Under these rules, 30 and 95 nonequivalent conformers occur for *n*-heptane and *n*-octane, respectively.

In the present work, we will first obtain benchmark ab initio conformer energies for *n*-butane, *n*-pentane, and *n*-hexane using large basis set CCSD(T) as a primary standard. We will then show that double-hybrid functionals[17,18] supplemented by an empirical dispersion correction yields results of essentially the same quality and will proceed to use these as a secondary standard. Next, we will consider the performance of a variety of density functional methods for the conformers of the pentanes, hexanes, and selected heptanes and octanes. Finally, we will address the quality of computed thermodynamic corrections both by the more rigorous and the more approximate methods.

II. Computational Methods

A. Electronic Structure. All calculations were carried out using MOLPRO 2008.1[19] or a locally modified version of Gaussian 03, rev. E.01[20] running on the Martin group Linux cluster at Weizmann. Gaussian was used for all DFT calculations as well as for MP2 optimizations; MOLPRO was used for the CCSD(T) calculations. Some post-CCSD(T) calculations were carried out using MRCC.[21]

The following DFT functionals were considered (grouped by rungs on the Jacob's Ladder of Perdew[22]):

- second rung (i.e., GGAs): BLYP,[23,24] PBE[25]
- third rung (i.e., meta-GGAs): M06L[26]
- imperfect fourth rung (i.e., hybrid GGAs): B3LYP,[27,28] B3PW91,[27,29] PBE0[30]
- full fourth rung (i.e., hybrid meta-GGAs): B1B95,[23,31] PW6B95,[32] BMK,[33] M06,[34] M06−2X[34]
- fifth rung: the double hybrids B2-PLYP,[17] B2GP-PLYP,[18] and B2K-PLYP[35]

Most wave function ab initio calculations were carried out using the cc-pVnZ[36] and aug-cc-pVnZ[37] basis sets of Dunning and co-workers. In the course of this paper, we will refer to the cc-pVnZ basis set by the PVnZ acronym and to the combination of aug-cc-pVnZ on carbon with regular cc-pVnZ on hydrogen by the A′VnZ acronym (n = D, T, Q).

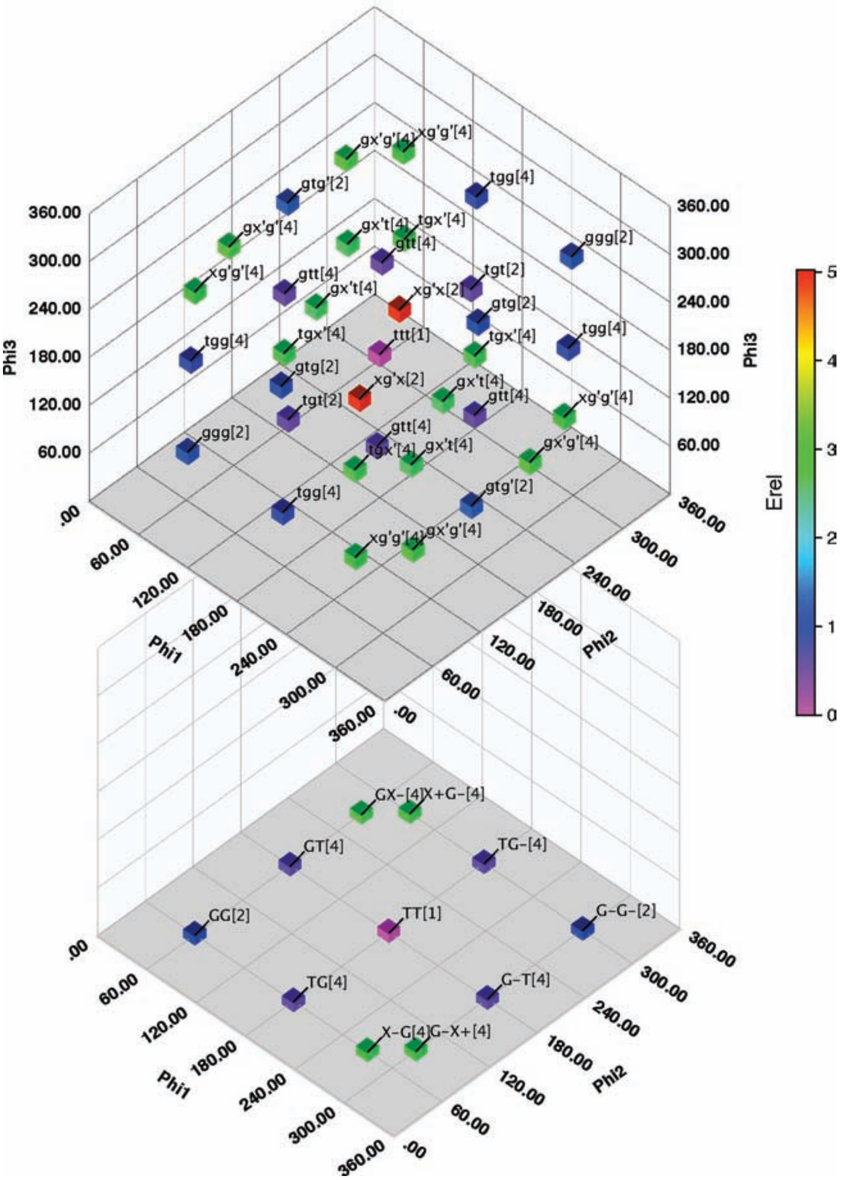

Figure 1. Graphical representation of the conformers of *n*-pentane (bottom) and *n*-hexane (top). The more purple the marker, the lower the conformer is in energy (kcal/mol). Degeneracies are noted in square brackets.

Most DFT calculations were carried out using the Jensen pc-2 basis set.[38]

Dispersion corrections for the DFT energies (denoted by the suffix -D) were applied using our implementation of Grimme's expression[39,40]

$$E_{\mathrm{disp}} = -s_6 \sum_{i=1}^{N_{\mathrm{at}}-1} \sum_{j=i+1}^{N_{\mathrm{at}}} \frac{C_6^{ij}}{R_{ij}^6} f_{\mathrm{dmp}}(R_{ij}) \qquad (1)$$

where the damping function is taken as

$$f_{\mathrm{dmp}}(R_{ij}) = \left[1 + \exp\left(-\alpha\left(\frac{R_{ij}}{s_{\mathrm{R}} R_{\mathrm{r}}} - 1\right)\right)\right]^{-1} \qquad (2)$$

and $C_6^{ij} \approx (C_6^i C_6^j)^{1/2}$, $R_{\mathrm{r}} = R_{\mathrm{vdW},i} + R_{\mathrm{vdW},j}$ is the sum of the van der Waals radii of the two atoms in question, and the specific numerical values for the atomic Lennard-Jones constants C_6^i and the van der Waals radii (in this case, 1.452 Å for C and 1.001 Å for H) have been taken from ref 39. The length scaling $s_{\mathrm{R}} = 1.0$ and hysteresis exponent $\alpha = 20.0$ were set as in ref 40.

This expression is left with a single functional-dependent empirical parameter, namely, the prefactor s_6. This was taken from refs 39 and 40 for BLYP, B3LYP, and PBE, from ref 18 for the double hybrids, and from ref 41 for the remaining functionals. These were, for the most part, optimized against the S22 benchmark set of weakly interacting systems.[42]

No corrections for intramolecular basis set superposition error (BSSE) were made; instead, we elected to use sufficiently large basis sets (spdf or spdfg quality), so that this should not be an issue on the accuracy scale of interest to us presently. We note that Balabin[43] studied intramolecular BSSE for trans/gauche butane and selected hexanes in considerable detail.

B. Other Aspects. The initial conformer structures were generated by stepping the CCCC dihedral angles in 30° increments, running molecular mechanics optimizations on all structures generated, and collating equivalent structures. In this manner, both the unique conformer structures and their degeneracies were obtained in an automated fashion.

The statistical thermodynamic corrections were then obtained by state summation according to the method of Pitzer and Brewer.[44] That is, the partition function and its first two moments were obtained as follows

$$Q = \sum_i d_i \exp\left(-\frac{E_i - E_0}{RT}\right) \tag{3}$$

$$Q' = \sum_i d_i\left(\frac{E_i - E_0}{RT}\right) \exp\left(-\frac{E_i - E_0}{RT}\right) \tag{4}$$

$$Q'' = \sum_i d_i\left(\frac{E_i - E_0}{RT}\right)^2 \exp\left(-\frac{E_i - E_0}{RT}\right) \tag{5}$$

where E_i and E_0 are the energies of state i and the ground state, respectively (in molar units), R is the gas constant (replace by the Boltzmann constant k if molecular units are preferred for the energies), d_i is the degeneracy of the state, and T is the temperature in Kelvin. The various thermodynamic functions are then obtained as

$$\text{gef}(T) \equiv -\frac{G_T - H_0}{T} = R \ln Q \tag{6}$$

$$\text{hcf}(T) = H_T - H_0 = RTQ'/Q \tag{7}$$

$$S(T) = R\left(\frac{Q'}{Q} + \ln Q\right) \tag{8}$$

$$C_p(T) = R\left(\frac{Q''}{Q} - \left(\frac{Q'}{Q}\right)^2\right) \tag{9}$$

A slight complication is introduced when the internal partition function is not assumed to be factorizable, that is, each of the conformers is allowed to have distinct rotational, vibrational, and (ignored in this work) electronic partition functions. Then, the following product rules apply (eqs 1−3 in ref 45)

$$Q = Q_0 + \sum_i \exp(-x_i)Q_i \tag{10}$$

$$Q' = Q'_0 + \exp(-x_i)[x_iQ_i + Q'_i] \tag{11}$$

$$Q'' = Q''_0 + \exp(-x_i)[x_i^2Q_i + Q''_i + 2x_iQ'_i] \tag{12}$$

where the shorthand $x_i \equiv (E_i - E_0)/RT$ was applied.

While the expression for $C_p(T)$ is too clumsy for practical use, the following equations express gef(T) and hcf(T) $\equiv H_T - H_0$ in terms of the quantities for the individual conformers

$$\text{gef}(T) = \text{gef}(T)_0 + R \ln\left[1 + \sum_i d_i \exp(-x_i)\frac{Q_i}{Q_0}\right] \tag{13}$$

$$\text{hcf}(T) = \frac{\text{hcf}_0(T) + \sum_i \exp(-x_i)\frac{Q_i}{Q_0}[RTx_i + \text{hcf}_i(T)]}{1 + \sum_i \exp(-x_i)\frac{Q_i}{Q_0}} \tag{14}$$

III. Results and Discussion

A. Wave Function Ab Initio. The wave function ab initio results are gathered in Table 2. (Results in this section apply to MP2/cc-pVTZ reference geometries).

1. n-Butane and n-Pentane. Applying W1 extrapolation[46] to CCSD(T)/PV{D,T}Z and CCSD/PV{T,Q}Z energies results in 0.598 kcal/mol. This is basically identical to our best result, 0.596 kcal/mol, which is obtained by W2 extrapolation[46] to CCSD(T)/PV{T,Q}Z and CCSD/PV{Q,5}Z data. At the CCSD(T)/A′VQZ level, the trans−gauche conformer separation is 0.609 kcal/mol. The CCSD(T)/PVQZ result is insignificantly different (0.606 kcal/mol), as is the CCSD(T)/A′VTZ result (0.613 kcal/mol). CCSD(T)/PVTZ still comes quite close at 0.588 kcal/mol (less than 0.01 kcal/mol below our best number); smaller basis sets exhibit more significant deviations (0.721 kcal/mol for A′VDZ, 0.693 kcal/mol for PVDZ). Our best value is in excellent agreement with the experimental value of 0.67 ± 0.10 kcal/mol of Herrebout et al.[10] as well as the best calculation of 0.62 kcal/mol by Allinger et al.[3] and the 0.628 kcal/mol obtained by Klauda et al.[47] at what they term the MP2:CC level. (This is their shorthand for a procedure that is essentially MP2/PVQZ + [CCSD(T)/PVDZ − MP2/PVDZ] at MP2/PVDZ reference geometries).

Let us now consider the n-particle convergence with the cc-pVTZ basis set. SCF, as expected, overestimates the separation at 1.138 kcal/mol, while MP2 slightly overcorrects at 0.561 kcal/mol. However, the accidental very good agreement with the CCSD(T) number of 0.588 kcal/mol results from a fortunate error compensation; the gap widens to 0.664 kcal/mol at the MP3 level, to 0.635 kcal/mol at the MP4(SDQ) level, and to 0.653 kcal/mol at the CCSD level.

We considered the effect of post-CCSD(T) correlation by carrying out CCSDT(Q)/cc-pVDZ(no p on H) calculations for both the trans and the gauche structures. Connected quadruple excitations (Q) and higher-order triple excitation effects (i.e., the CCSDT − CCSD(T) difference) are found to stabilize the gauche conformer by just 0.002 kcal/mol each; we conclude that post-CCSD(T) effects are insignificant on the accuracy scale in which we are interested.

In the case of n-pentane, our best (W1h-val-type) estimates for the conformer energies of {TG, GG, and GX$^-$ } relative to TT are {0.614, 0.961, 2.813} kcal/mol, only marginally different from numbers obtained from (T) contributions with the AVTZ basis set and CCSD contributions with the PVQZ basis set, {0.605, 0.954, 2.810} kcal/mol. As expected, the CCSD(T)/AVTZ numbers are close at {0.586, 0.946, 2.817} kcal/mol, as are the CCSD(T)/PVTZ numbers at {0.581, 0.919, 2.767} kcal/mol, even though the latter hint at an undershooting problem that will become clearer for n-hexane. The same general trends as those for n-butane apply to n-particle convergence; MP2 slightly overcorrects, and CCSD spaces conformers too wide. The MP2 error is largest for the GG conformer; the (T) contributions for the GG and GX$^-$ conformer energies are noticeably larger than that for TG. The TG and GG values are in excellent agreement with the latest measurements by Balabin,[13] 0.618 ± 0.006 and 0.940 ± 0.020 kcal/mol, respectively.

TABLE 2: Relative Energies (in kcal/mol) of *n*-Butane, *n*-Pentane, and *n*-Hexane Conformers at MP2/cc-pVTZ Reference Geometries

		cc-pVTZ					aug-cc-pVTZ		cc-pVQZ						
		HF	MP2	SCS-MP2	CCSD	CCSD(T)	CCSD	CCSD(T)	HF	MP2	SCS-MP2	CCSD	CCSD(T)	W1h-val[a]	MP2:CC
									n-Butane						
T	C_{2h}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G	C_2	1.138	0.561	0.657	0.653	0.588	0.679	0.613	1.147	0.578	0.674	0.673	0.606	0.611[b]	0.620
									n-Pentane						
TT	C_{2v}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000
TG	C_1	1.191	0.548	0.654	0.658	0.581	0.664	0.586	1.201	0.569	0.675	0.684		0.614	0.613
GG	C_2	2.388	0.778	1.072	1.096	0.919	1.127	0.946	2.407	0.804	1.104	1.136		0.961	0.977
GX$^-$	C_1	4.275	2.783	2.972	2.957	2.767	3.008	2.817	4.292	2.811	3.002	3.002		2.813	2.833
									n-Hexane						
TTT	C_{2h}	0.000	0.000	0.000	0.000	0.000			0.000	0.000	0.000	0.000		0.000	0.000
GTT	C_1	1.203	0.517	0.633	0.639	0.558			1.213	0.539	0.656	0.666		0.595	0.589
TGT	C_2	1.249	0.517	0.642	0.649	0.561			1.262	0.543	0.669	0.682		0.604	0.595
TGG	C_1	2.499	0.706	1.033	1.070	0.871			2.521	0.741	1.076	1.124		0.934	0.930
GTG	C_2	2.408	1.011	1.243	1.262	1.101			2.428	1.057	1.292	1.320		1.178	1.165
G$^+$T$^+$G$^-$	C_i	2.481	1.179	1.399	1.398	1.240			2.501	1.218	1.439	1.447		1.302	1.305
GGG	C_2	3.696	0.914	1.429	1.487	1.180			3.727	0.951	1.482	1.553		1.250	1.260
G$^+$X$^-$T$^+$	C_1	4.282	2.554	2.805	2.802	2.584			4.301	2.580	2.835	2.848		2.632	2.646
T$^+$G$^+$X$^-$	C_1	4.343	2.654	2.885	2.878	2.660			4.363	2.699	2.934	2.942		2.740	2.733
G$^+$X$^-$G$^-$	C_1	5.492	3.143	3.498	3.504	3.209			5.518	3.185	3.545	3.571		3.283	3.293
X$^+$G$^-$G$^-$	C_1	5.666	2.912	3.357	3.354	3.013			5.702	2.952	3.405	3.424		3.083	3.105
X$^+$G$^-$X$^+$	C_2	7.787	4.860	5.275	5.237	4.855			7.824	4.900	5.322	5.312		4.925	4.947

[a] SCF and CCSD energies extrapolated from cc-pV{T,Q}Z basis set pair and the (T) contribution extrapolated from the cc-pV{D,T}Z basis set pair. [b] Using the augmented basis sets results in 0.598 kcal/mol.

SCS-MP2[48] yields conformer relative energies that are basically indistinguishable from CCSD.

Klauda et al.[47] report MP2:CC numbers of {0.622, 0.985, 2.846} kcal/mol, which are quite close to our higher-level data. Our own MP2:CC calculation at our higher-level (MP2/cc-pVTZ) geometries yields slightly different numbers.

Our best estimates are somewhat different from those of Salam and Deleuze, {0.621, 1.065, 2.917} kcal/mol. Detailed analysis suggests that these differences are primarily due to their use of B3LYP/6-311++G(d,p) reference geometries. We shall see below that the B3LYP functional is inadequate for this purpose, not just in relative energies which are {0.855, 1.604, 3.360} at the B3LYP/6-311++G(d,p) level but also in terms of the calculated geometries; as can be seen in Table 4, the backbone torsion angles for the GG and GX$^-$ conformers are off by 5−6°.

SCS-MP2 tracks the CCSD numbers quite closely, while SCS-CCSD clearly overcorrects for the (T) contribution.

The TT − GG energy difference appears to be the most sensitive to the level of theory, followed by the TT − GX$^-$ difference.

2. n-Hexane. *n*-Hexane, with its 12 conformers, becomes a bit unwieldy to compare in terms of individual conformer energies. One could instead focus on the calculated conformer contribution to the enthalpy function, which is the quantity that interests us most from a utilitarian point of view. However, by construction, this will be most affected by the low-lying gtt and tgt conformers.

Let us first consider the relative energies of the conformers at the W1h-val level. Obviously, the ttt conformer is lowest in energy, followed by nearly isoenergetic gtt and tgt conformers. Somewhat higher up is tgg, which is markedly more stable than gtg. The gtg$^-$ is about 0.13 kcal/mol less stable than its cousin gtg, while ggg finds itself sandwiched between them. The remaining five conformers all have at least one "pentane interference" interaction; gxt and tgx$^-$ are nearly isoenergetic (and about 1.4 kcal/mol less stable than ggg), as is the less stable xg$^-$g$^-$ and gxg$^-$ pair, while the least stable conformer is xg$^-$x. Visual inspection reveals (see Supporting Information) that this latter conformer is basically a "helix", one end nearly coiling back over the other.

Klauda et al.[47] calculated MP2:CC relative energies for selected conformers: tgt 0.600, tgg 0.930, tgg$^-$ 2.740, gtg 1.180, gtg$^-$ 1.320 kcal/mol. We computed a complete set (Table 2) at our own reference geometries and found MP2:CC to agree with our W1h-val data to within about 0.01 kcal/mol. In contrast, CCSD(T)/cc-pVTZ data are biased downward by as much as 0.1 kcal/mol, presumably due to basis set superposition error.

B. Density Functional Methods. In order to basically eliminate the basis set as a factor in our comparison, we have used the extended pc-2 basis set throughout. Except for the double-hybrid results, a full optimization was carried out for every functional.

Let us begin by considering the pentane and hexane conformers. The energetic data are collected in Table 3.

A few interesting features emerge. First, the percentage of Hartree−Fock exchange does not seem to be all that important; the BLYP/B3LYP pair on the one hand, and the PBE/PBE0 pair on the other hand, yield basically the same answers.

Second, while conventional DFT functionals (such as B3LYP, PBE0, B3PW91,...) tend to overestimate conformer gaps (progressively more so as one goes higher up the conformer ladder), the M06 family of Truhlar underestimates them. Of particular note is the situation in pentane, where M06 wrongly finds the TG and GG conformers to be energetically nearly degenerate. Similarly distorted energetic pictures are seen for hexane conformers; we note, from considering the Grimme dispersion corrections for the various structures, that the GG interaction is favored by dispersion, and it appears that the M06 family overestimates that impact. The PW6B95 and BMK functionals, on the other hand, surprisingly do a much better job.

Third, it was previously noted[50] that Grimme-type empirical dispersion corrections considerably improved DFT relative energies for selected conformers of 4-ethyl-4-methyloctane. Comparing with a larger sample of higher-level reference data, however, we find that Grimme-type corrections appear to

TABLE 3: Comparison between Various DFT Functionals (pc-2 basis set, without dispersion correction) and Our Best Conformer Energies (kcal/mol) for *n*-Butane, *n*-Pentane, and *n*-Hexane

	ref[a]	B1B95	B3LYP	BLYP	M06L	M06	M06-2X	PBE0	PBE	PW6B95	B2GP-PLYP	B2K-PLYP	B2-PLYP	BMK	B3PW91	MP2[b]
n-Butane																
T	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
G	0.598	0.778	0.898	0.925	0.393	0.466	0.522	0.820	0.813	0.712	0.986	0.990	0.986	0.703	0.968	0.561
n-Pentane																
TT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TG	0.614	0.771	0.912	0.938	0.439	0.526	0.578	0.826	0.813	0.712	0.749	0.724	0.790	0.595	0.922	0.548
GG	0.961	1.239	1.665	1.737	0.339	0.449	0.581	1.444	1.433	1.079	1.383	1.294	1.537	1.048	1.665	0.778
GX^-	2.813	3.131	3.459	3.417	2.433	2.467	2.585	3.345	3.220	2.947	3.226	3.174	3.312	2.868	3.565	2.783
n-Hexane																
TTT	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GTT	0.595	0.768	0.905	0.928	0.355	0.427	0.502	0.820	0.803	0.702	0.726	0.699	0.773	0.651	0.914	0.517
TGT	0.604	0.808	0.942	0.960	0.441	0.500	0.541	0.861	0.839	0.745	0.750	0.719	0.804	0.745	0.957	0.517
TGG	0.934	1.361	1.763	1.839	0.400	0.527	0.641	1.542	1.536	1.193	1.410	1.306	1.586	1.143	1.769	0.706
GTG	1.178	1.548	1.834	1.884	0.783	0.893	1.004	1.665	1.640	1.415	1.477	1.417	1.580	1.326	1.855	1.011
$G^+T^+G^-$	1.302	1.608	1.871	1.908	0.845	1.065	1.178	1.714	1.669	1.479	1.563	1.517	1.641	1.454	1.890	1.179
GGG	1.250	1.823	2.595	2.728	0.390	0.594	0.751	2.238	2.252	1.561	1.983	1.822	2.258	1.586	2.597	0.914
$G^+X^-T^+$	2.632	3.019	3.421	3.390	2.241	2.303	2.339	3.260	3.148	2.820	3.066	3.001	3.177	2.919	3.502	2.554
$T^+G^+X^-$	2.740	3.122	3.449	3.419	2.325	2.359	2.468	3.318	3.181	2.922	3.130	3.068	3.233	2.907	3.549	2.654
$G^+X^-G^-$	3.283	3.737	4.313	4.317	2.647	2.815	2.953	4.051	3.915	3.498	3.818	3.730	3.966	3.458	4.371	3.143
$X^+G^-G^-$	3.083	3.713	4.376	4.422	2.216	2.432	2.631	4.072	3.947	3.386	3.725	3.613	3.915	3.270	4.497	2.912
$X^+G^-X^+$	4.925	5.566	6.227	6.207	4.199	4.480	4.514	5.957	5.734	5.199	5.593	5.501	5.750	5.179	6.406	4.860
rmsd[c]		0.44	0.90	0.93	0.57	0.41	0.31	0.69	0.61	0.22	0.47	0.38	0.61	0.20	0.97	0.16
With Standard "-D" Dispersion Correction																
rmsd[d]		0.86	0.90	1.13	0.91	0.84	0.31	0.52	0.69	0.64	0.21	0.13	0.34	0.92	0.09	0.15
s_6		0.75	1.05	1.20	0.20	0.25	0.00	0.70	0.75	0.50	0.40	0.30	0.55	0.65	1.10	(−0.16)
With Ad Hoc Dispersion Correction																
rmsd[e]		0.04	0.03	0.06	0.06	0.06	0.04	0.03	0.05	0.04	0.02	0.02	0.05	0.06	0.05	
s_6		0.25	0.52	0.54	(−0.33)	(−0.24)	(−0.18)	0.40	0.35	0.13	0.28	0.22	0.36	0.11	0.56	

[a] Best values from Table 2; W1h-val throughout. [b] The cc-pVTZ basis set. [c] Over the *n*-hexane conformers, without dispersion correction. [d] Over the *n*-hexane conformers, with dispersion correction using standard s_6 values for the functionals (see text) given in the subsequent row. [e] Over the *n*-hexane conformers, with dispersion correction using ad hoc optimized s_6 values given in the subsequent row. Negative s_6 values can be seen as "undoing" an overcorrection in the underlying level of theory.

TABLE 4: Backbone Torsion Angles (degree) of the *n*-Pentane Conformers Obtained with Different DFT Functionals in Conjunction with the pc-2 Basis Set

conformer	τ	B1B95	B3LYP	B3PW91	BLYP	BMK	M06-2X	M06-L	M06	PBE0	PBE	PW6B95	MP2[a]
TG	τ_1	177.1	177.3	177.3	177.4	177.0	175.3	177.2	175.2	177.2	177.3	176.9	176.2
	τ_2	64.7	66.2	66.0	66.8	64.1	61.6	62.3	62.7	65.3	65.7	64.5	64.0
GG	τ_1	56.5	63.6	63.1	64.9	58.5	56.6	58.0	58.5	61.7	62.8	56.5	58.3
GX^-	τ_1	−98.3	−90.9	−90.9	−89.3	−97.8	−95.8	−92.5	−94.4	−93.9	−91.7	−98.0	−96.4
	τ_2	59.3	65.0	65.0	67.1	59.1	58.6	59.2	61.8	62.3	64.1	59.3	59.9

[a] The cc-pVTZ basis set.

overcorrect for the conventional DFT functionals. Ad hoc reoptimization of s_6 prefactors revealed that, for alkane conformer energies, one would like a prefactor about 0.4−0.5 smaller than the generic optimum. For the M06 family, ad hoc optimized s_6 values are actually negative, which can be seen as "undoing" an overcorrection for dispersion.

Detailed inspection of dispersion correction contributions for the simplest case (the trans−gauche equilibrium in butane) reveals that dispersion interactions between the terminal CH_3 group and the CH_2 group in the β position relative to it ("1,3" interactions, if one likes) actually favor the trans conformer (as it has two β-hydrogens in close proximity rather than one) but that the gauche conformer enjoys much more favorable "1,4" dispersion interactions. The 1,3-interactions are in the distance range where the damping function, eq 2, rapidly turns over, making the overall correction quite sensitive to its details. In addition some double-counting with the DFT correlation functional is inevitable.

Fourth, the double-hybrids B2GP-PLYP and B2K-PLYP perform fairly well even without dispersion corrections and very well when supplemented with their standard dispersion corrections ($s_6 = 0.40$ for B2GP-PLYP-D and 0.30 for B2K-PLYP-D). Ad hoc optimization results in s_6 values that, unlike for the conventional functionals, are only slightly smaller than the standard values, $s_6 = 0.28$ for B2GP-PLYP and $s_6 = 0.22$ for B2K-PLYP. (Note that if CCSD(T)/cc-pVTZ reference data were used instead for calibration, higher s_6 values of 0.32 for B2GP-PLYP and 0.26 for B2K-PLYP would result, which would lead to a downward bias for all conformer energies.) These results once again underline the robustness and versatility of the B2GP-PLYP and B2K-PLYP functionals. After ad hoc adjustment of s_6, the various double hybrids yield results of comparable quantity. In the remainder of the paper, we have somewhat arbitrarily restricted ourselves to B2K-PLYP as it requires the smallest adjustment to s_6, but we could have used B2GP-PLYP to equally good effect.

Fifth, the deficiencies of several functionals are not just reflected in the energetics but also in the geometries. This is especially noticeable in the backbone torsion angles. Table 4 contains the dihedral angles for the TG, GG, and GX^- conformers of *n*-pentane by way of illustration.

As MP2/cc-pVTZ optimizations for all heptane and especially octane conformers would be computationally too unwieldy, we selected the PW6B95 functional for optimizing the reference geometries of the remaining conformers. Some exploratory calculations on pentane and hexane revealed that the 6-311G**

TABLE 5: Relative Energies, Point Groups, And Degeneracies of the *n*-Octane, *n*-Heptane, Isohexane, 3-Methylpentane, Isooctane, Isoheptane, Neopentane, And Isopentane Conformers at the B2K-PLYP-D(0.22)/pc-2//PW6B95/6-311G(d,p) Level of Theory (in kcal/mol)

degen.	conformer	symm.	energy	degen.	conformer	symm.	energy	degen.	conformer	symm.	energy	degen.	conformer	symm.	energy
	n-Octane				*n*-Octane				*n*-Heptane				Isoheptane		
1	TTTTT	C_{2h}	0.000	4	$\mathrm{G^{-}G^{-}TG^{-}X^{+}}$	C_1	3.572	1	TTTT	C_{2v}	0.000	2	$\mathrm{TTG^{-}}$	C_1	0.000
4	$\mathrm{TTTTG^{-}}$	C_1	0.584	4	$\mathrm{G^{+}TG^{+}G^{+}X^{-}}$	C_1	3.416	4	$\mathrm{TTTG^{-}}$	C_1	0.581	2	$\mathrm{TG^{+}T}$	C_1	0.306
2	$\mathrm{TTG^{-}TT}$	C_2	0.545	4	$\mathrm{G^{-}G^{-}TX^{-}G^{+}}$	C_1	3.538	4	$\mathrm{TTG^{-}T}$	C_1	0.570	1	$\mathrm{TTG^{+}}$	C_s	0.778
4	$\mathrm{TTTG^{-}T}$	C_1	0.556	4	$\mathrm{TTG^{-}X^{+}G^{+}}$	C_1	3.164	4	$\mathrm{TTG^{-}G^{-}}$	C_1	0.916	2	$\mathrm{G^{+}TT}$	C_1	0.539
4	$\mathrm{TTG^{-}G^{-}T}$	C_1	0.822	4	$\mathrm{TX^{+}G^{-}TG^{+}}$	C_1	3.274	2	$\mathrm{TG^{+}G^{+}T}$	C_2	0.860	2	$\mathrm{G^{+}G^{+}T}$	C_1	0.600
4	$\mathrm{TTTG^{-}G^{-}}$	C_1	0.890	4	$\mathrm{TG^{+}G^{+}G^{+}X^{-}}$	C_1	3.369	4	$\mathrm{TG^{+}TG^{+}}$	C_1	1.140	2	$\mathrm{G^{+}TG^{-}}$	C_1	0.690
4	$\mathrm{TTG^{-}TG^{-}}$	C_1	1.098	4	$\mathrm{TTG^{-}X^{-}G^{+}}$	C_1	3.262	2	$\mathrm{G^{+}TTG^{+}}$	C_2	1.148	2	$\mathrm{G^{+}TG^{+}}$	C_1	1.445
2	$\mathrm{TG^{+}TG^{+}T}$	C_2	1.099	4	$\mathrm{TG^{+}X^{-}G^{-}T}$	C_1	3.136	2	$\mathrm{G^{+}TTG^{-}}$	C_s	1.152	2	$\mathrm{TX^{+}G^{-}}$	C_1	2.047
2	$\mathrm{G^{+}TTTG^{+}}$	C_2	1.159	4	$\mathrm{G^{+}G^{+}TX^{-}G^{+}}$	C_1	3.594	4	$\mathrm{TG^{+}TG^{-}}$	C_1	1.265	2	$\mathrm{TG^{+}X^{-}}$	C_1	2.426
4	$\mathrm{TG^{+}TTG^{+}}$	C_1	1.118	4	$\mathrm{TX^{+}G^{-}G^{-}G^{-}}$	C_1	3.224	4	$\mathrm{TG^{+}G^{+}G^{+}}$	C_1	1.186	2	$\mathrm{TG^{+}G^{+}}$	C_1	3.025
2	$\mathrm{G^{+}TTTG^{-}}$	C_i	1.156	4	$\mathrm{TG^{+}TG^{-}X^{+}}$	C_1	3.424	4	$\mathrm{G^{+}TG^{+}G^{+}}$	C_1	1.447	2	$\mathrm{X^{+}G^{-}G^{-}}$	C_1	2.480
4	$\mathrm{TTG^{-}G^{-}G^{-}}$	C_1	1.123	4	$\mathrm{G^{+}G^{+}X^{-}TG^{-}}$	C_1	3.431	2	$\mathrm{G^{+}TG^{-}G^{-}}$	C_1	1.606	3	$\mathrm{TX^{+}G^{+}}$	C_1	2.784
2	$\mathrm{TG^{+}G^{+}G^{+}T}$	C_2	1.071	4	$\mathrm{G^{+}TG^{-}G^{-}X^{+}}$	C_1	3.567	4	$\mathrm{G^{+}G^{+}G^{+}G^{+}}$	C_2	1.519	2	$\mathrm{G^{+}X^{-}G^{-}}$	C_1	2.567
4	$\mathrm{TG^{+}TTG^{-}}$	C_1	1.117	4	$\mathrm{G^{+}G^{+}TG^{-}X^{+}}$	C_1	3.724	4	$\mathrm{TTX^{-}G^{+}}$	C_1	2.674	2	$\mathrm{G^{+}G^{+}C^{+}}$	C_1	3.404
4	$\mathrm{TG^{+}G^{+}TG^{+}}$	C_1	1.343	4	$\mathrm{TG^{+}G^{+}X^{-}G^{-}}$	C_1	3.192	4	$\mathrm{TTG^{-}X^{+}}$	C_1	2.740	2	$\mathrm{G^{+}X^{+}G^{-}}$	C_1	2.627
4	$\mathrm{TG^{+}TG^{+}G^{+}}$	C_1	1.368	4	$\mathrm{G^{+}TX^{-}G^{+}G^{+}}$	C_1	3.591	4	$\mathrm{TG^{+}X^{-}T}$	C_1	2.608	2	$\mathrm{G^{+}G^{+}X^{-}}$	C_1	2.779
4	$\mathrm{TTG^{-}TG^{+}}$	C_1	1.229	4	$\mathrm{G^{+}G^{+}G^{+}G^{+}X^{-}}$	C_1	3.702	4	$\mathrm{TG^{+}G^{+}X^{-}}$	C_1	2.956	2	$\mathrm{G^{+}X^{+}G^{+}}$	C_1	3.466
4	$\mathrm{G^{+}TTG^{+}G^{+}}$	C_1	1.430	4	$\mathrm{G^{+}TG^{+}X^{-}G^{-}}$	C_1	3.778	4	$\mathrm{TX^{+}G^{-}G^{-}}$	C_1	2.917	2	$\mathrm{X^{+}G^{-}T^{-}}$	C_1	4.577
4	$\mathrm{G^{-}TTG^{+}G^{+}}$	C_1	1.434	4	$\mathrm{TG^{+}X^{+}G^{-}G^{-}}$	C_1	3.279	4	$\mathrm{G^{+}TX^{+}G^{-}}$	C_1	3.261		Neoheptane		
2	$\mathrm{TG^{+}TG^{-}T}$	C_i	1.246	4	$\mathrm{G^{+}TG^{+}X^{+}G^{-}}$	C_1	3.795	8	$\mathrm{G^{+}TG^{+}X^{-}}$	C_1	3.329	1	T	C_s	0.000
2	$\mathrm{G^{+}TG^{+}TG^{+}}$	C_2	1.685	4	$\mathrm{G^{+}TX^{-}X^{-}G^{+}}$	C_1	3.821	4	$\mathrm{G^{+}TX^{-}G^{+}}$	C_1	3.332	2	$\mathrm{X^{-}}$	C_1	2.256
2	$\mathrm{G^{+}G^{+}TG^{+}G^{+}}$	C_2	1.656	4	$\mathrm{TG^{+}X^{-}G^{-}G^{-}}$	C_1	3.793	8	$\mathrm{TG^{+}X^{+}G^{-}}$	C_1	3.280	2	$\mathrm{G^{-}}$	C_1	2.708
4	$\mathrm{TG^{+}G^{+}G^{+}G^{+}}$	C_1	1.413	4	$\mathrm{G^{-}X^{-}G^{+}G^{+}G^{+}}$	C_1	3.736	4	$\mathrm{TG^{+}X^{-}G^{-}}$	C_1	3.220		Isopentane		
4	$\mathrm{G^{-}G^{-}G^{-}TG^{-}}$	C_1	1.634	4	$\mathrm{G^{+}TG^{-}X^{+}G^{+}}$	C_1	3.881	4	$\mathrm{G^{+}G^{+}G^{+}X^{-}}$	C_1	3.506	2	$\mathrm{G^{+}}$	C_1	0.000
4	$\mathrm{TG^{+}G^{+}TG^{-}}$	C_1	1.495	4	$\mathrm{G^{+}G^{+}G^{+}X^{+}G^{-}}$	C_1	4.115	4	$\mathrm{G^{+}G^{+}X^{-}G^{-}}$	C_1	3.413	1	$\mathrm{G^{-}}$	C_s	0.786
4	$\mathrm{TG^{+}TG^{-}G^{-}}$	C_1	1.574	4	$\mathrm{G^{+}G^{+}X^{-}G^{-}G^{-}}$	C_1	3.863	2	$\mathrm{TX^{+}G^{-}X^{+}}$	C_1	4.636		Isooctane		
4	$\mathrm{G^{+}TG^{-}TG^{-}}$	C_1	1.822	4	$\mathrm{TG^{+}X^{-}X^{-}G^{+}}$	C_1	4.804	4	$\mathrm{G^{+}X^{-}X^{-}G^{+}}$	C_2	4.897	2	$\mathrm{X^{-}}$	C_1	0.000
2	$\mathrm{G^{+}G^{+}G^{+}G^{+}G^{+}}$	C_2	1.752	2	$\mathrm{TX^{+}G^{-}X^{+}T}$	C_2	4.223	4	$\mathrm{G^{+}X^{+}G^{-}X^{+}}$	C_1	5.426	2	$\mathrm{G^{-}}$	C_1	0.483
4	$\mathrm{G^{+}TG^{-}G^{-}G^{-}}$	C_1	1.805	4	$\mathrm{TTX^{-}G^{+}X^{-}}$	C_1	4.560	4	$\mathrm{L^{+}G^{-}X^{-}G^{+}}$	C_1	6.051	2	$\mathrm{X^{+}}$	C_1	3.319
2	$\mathrm{G^{+}G^{+}TG^{-}G^{-}}$	C_i	1.908	2	$\mathrm{G^{+}X^{-}TX^{-}G^{+}}$	C_2	5.212	2	$\mathrm{X^{+}G^{-}G^{-}X^{+}}$	C_2	6.288				
2	$\mathrm{G^{+}TG^{-}TG^{+}}$	C_2	1.959	4	$\mathrm{G^{+}G^{+}X^{-}X^{-}G^{+}}$	C_1	5.183		Isohexane						
4	$\mathrm{TTTX^{-}G^{+}}$	C_1	2.658	2	$\mathrm{X^{+}G^{-}TG^{-}X^{+}}$	C_2	5.508	2	$\mathrm{TG^{-}}$	C_1	0.000				
4	$\mathrm{TTG^{-}X^{+}T}$	C_1	2.507	4	$\mathrm{G^{+}TX^{+}G^{-}X^{+}}$	C_1	5.248	2	$\mathrm{G^{+}T}$	C_1	0.352				
4	$\mathrm{TTX^{-}G^{+}T}$	C_1	2.561	4	$\mathrm{X^{+}G^{-}TX^{+}G^{-}}$	C_1	5.469	1	$\mathrm{TG^{+}}$	C_s	0.803				
4	$\mathrm{TTTG^{-}X^{+}}$	C_1	2.713	4	$\mathrm{G^{+}TX^{-}G^{+}X^{-}}$	C_1	5.255	2	$\mathrm{X^{+}G^{-}}$	C_1	2.220				
4	$\mathrm{TTG^{-}G^{-}X^{+}}$	C_1	2.883	4	$\mathrm{X^{+}G^{-}TX^{-}G^{+}}$	C_1	5.488	2	$\mathrm{G^{+}X^{-}}$	C_1	2.533				
4	$\mathrm{TX^{+}G^{-}TG^{-}}$	C_1	3.140	4	$\mathrm{TX^{+}G^{-}X^{+}G^{+}}$	C_1	5.078	2	$\mathrm{G^{+}G^{+}}$	C_1	3.165				
4	$\mathrm{TX^{+}G^{-}G^{-}T}$	C_1	2.702	2	$\mathrm{G^{+}X^{-}TX^{+}G^{-}}$	C_i	5.544	2	$\mathrm{X^{+}G^{+}}$	C_1	2.983				
4	$\mathrm{TG^{+}TG^{+}X^{-}}$	C_1	3.303	4	$\mathrm{TX^{+}X^{+}G^{-}X^{+}}$	C_1	5.328		3-Methylpentane						
4	$\mathrm{G^{+}TTG^{+}X^{-}}$	C_1	3.255	2	$\mathrm{X^{+}G^{-}G^{-}G^{-}X^{+}}$	C_2	5.544	2	TG	C_1	0.353				
4	$\mathrm{G^{+}TTX^{-}G^{+}}$	C_1	3.171	2	$\mathrm{X^{+}G^{-}TG^{+}X^{-}}$	C_i	5.700	2	$\mathrm{G^{-}T}$	C_1	0.115				
4	$\mathrm{TTX^{-}G^{+}G^{+}}$	C_1	2.880	4	$\mathrm{X^{+}G^{-}G^{-}X^{-}G^{+}}$	C_1	5.803	2	$\mathrm{G^{-}G^{-}}$	C_1	0.630				
4	$\mathrm{G^{+}TTX^{+}G^{-}}$	C_1	3.228	2	$\mathrm{G^{+}X^{-}X^{-}X^{-}G^{+}}$	C_2	5.914	1	$\mathrm{G^{-}G^{+}}$	C_s	0.000				
4	$\mathrm{TG^{+}X^{-}TG^{-}}$	C_1	3.127	4	$\mathrm{TG^{+}X^{-}G^{-}L^{+}}$	C_1	5.913	2	$\mathrm{T^{-}T}$	C_1	1.862				
4	$\mathrm{G^{+}TTG^{-}X^{+}}$	C_1	3.254	4	$\mathrm{G^{+}G^{+}X^{+}G^{-}X^{+}}$	C_1	6.128	2	$\mathrm{C^{+}G^{-}}$	C_1	3.222				
4	$\mathrm{TG^{+}TX^{+}G^{-}}$	C_1	3.213	2	$\mathrm{G^{+}X^{+}G^{-}X^{+}G^{+}}$	C_2	5.942								
4	$\mathrm{TG^{+}X^{-}TG^{+}}$	C_1	3.237	4	$\mathrm{X^{+}G^{-}X^{+}X^{+}G^{-}}$	C_1	6.991								
4	$\mathrm{TG^{+}TX^{-}G^{+}}$	C_1	3.287	4	$\mathrm{L^{+}G^{-}X^{-}G^{+}X^{-}}$	C_1	8.083								

basis set was adequately converged for our purposes and that B2K-PLYP/pc-2 energetics at these reference geometries were very close to those obtained at MP2/cc-pVTZ geometries. The PW6B95/6-311G** level of theory was thus selected for the remaining conformer sets.

C. *n*-Heptane, *n*-Octane, and the Branched Alkanes. B2K-PLYP-D/pc-2//PW6B96/6-311G** relative conformer energies for all species considered in this paper can be found in Table 5. We shall briefly survey the conformer sets here. As an additional check on our procedure, we have calculated the *n*-heptane conformer energies at the MP2:CC level as well. These results are compared with the B2K-PLYP-D(0.22)/pc-2 data in Table S1 of the Supporting Information. The two sets of values are in very close agreement with each other, with an rmsd of just 0.04 kcal/mol. Refitting s_6 to this larger sample of 30 conformers revealed no significant change; $s_6 = 0.224$ rmsd and $s_6 = 0.214$ when fitted to RMSRelD, between which values $s_6 = 0.22$ is a good compromise. While *n*-heptane still has a pronounced "band gap" of sorts between the conformers involving only t and g interactions and the conformers involving $x^{\pm}g^{\mp}$ or $g^{\pm}x^{\mp}$ sequences, this gap becomes much smaller for *n*-octane.

Isopentane has just two conformers, the no-symmetry ground-state conformer (with a trans backbone skeleton) and, around 0.79 kcal/mol higher, a gauche-like conformer with C_s symmetry.

Isohexane (2-methylpentane) has seven conformers; these are best understood by substituting a methyl group on the four unique conformers of *n*-pentane. The ground-state conformer is TT; the TG and GT conformers become nonequivalent because of the methyl group; $\mathrm{GX^{-}}$ and $\mathrm{X^{-}G}$ likewise become nonequivalent; and unlike for *n*-pentane, the GG conformer is actually the highest in energy here.

Isoheptane has 18 conformers, which are again best understood by substituting a methyl group on the 12 unique conformers of *n*-hexane and considering the resulting loss of spatial degeneracy. Further details can be found in the Supporting Information.

Isooctane, the "100%" fixpoint on the octane scale, does not have the usual 2-methyl backbone structure of the lower isoalkanes but is effectively (*t*-butyl,isopropyl)methane. It has just three conformers, all without symmetry; in the global minimum, the *i*Pr and *t*BU groups are oriented anti with respect to each other (fairly close to C_s symmetry), while a gauche-

TABLE 6: Enthalpy Function ($H_{298} - H_0$) and Gibbs Energy Function Calculated with Various DFT Functionals with the pc-2 Basis Set[a]

	B1B95	B2K-PLYP	B2K-PLYP-D	B3LYP	BLYP	M06-2X	M06	M06-L	PBE	PBE0	PW6B95	CCSD(T)	W1h-val[b]
						$H_{298} - H_0$ (kcal/mol)							
n-butane	0.272	0.269	0.256	0.274	0.273	0.237	0.222	0.199	0.274	0.274	0.267	0.254	0.252
n-pentane	0.513	0.497	0.468	0.514	0.514	0.435	0.395	0.336	0.514	0.513	0.504	0.462	0.473
isopentane	0.090	0.090	0.092	0.085	0.083	0.093	0.093	0.087	0.086	0.087	0.091		
n-hexane	0.757	0.726	0.678	0.748	0.746	0.608	0.546	0.464	0.750	0.750	0.746	0.663	0.686
isohexane	0.267	0.269	0.243			0.164	0.170	0.148	0.278	0.271	0.261		
3-methylpentane	0.308	0.303	0.265	0.326	0.322	0.168	0.150	0.154	0.327	0.326	0.294		
diisopropyl	0.009	0.055	0.041	0.025	0.018	0.037	−0.075	−0.164	0.055	0.056	0.003		
n-heptane	1.005	0.960	0.886	0.942	0.921	0.840	0.837	0.649	0.966	0.974	0.991		0.893[c]
isoheptane	0.520	0.513	0.456	0.583	0.487	0.353	0.401	0.286	0.530	0.525	0.506		
neoheptane	0.160	0.129	0.147		0.138	0.223	0.221	0.257		0.115	0.183		
n-octane	1.250	1.190	1.076	1.178	1.153	0.946	0.942	1.250	1.209	1.250	1.222		
isooctane	0.167	0.161	0.156	0.169	0.170	0.147	0.128	0.134	0.167	0.167	0.164		
						Gibbs Energy Function (cal/K·mol)							
n-butane	0.856	0.910	1.053	0.724	0.696	1.199	1.286	1.407	0.815	0.808	0.935	1.073	1.088
n-pentane	1.704	1.758	2.090	1.367	1.317	2.379	2.570	2.805	1.576	1.550	1.864	2.135	2.080
isopentane	1.592	1.596	1.625	1.556	1.546	1.651	1.684	1.778	1.560	1.569	1.606		
n-hexane	2.454	2.632	3.166	1.982	1.917	3.654	3.927	4.264	2.283	2.238	2.708	3.286	3.148
isohexane	2.265	2.215	2.466			2.851	2.849	2.997	2.047	2.066	2.378		
3-methylpentane	2.808	2.797	3.004	2.543	2.506	3.408	3.471	3.458	2.579	2.614	2.897		
diisopropyl	2.153	1.993	2.043	2.099	2.124	2.056	2.427	2.706	1.993	1.991	2.172		
n-heptane	3.262	3.512	4.284	2.392	2.229	4.693	4.795	5.499	2.850	2.834	3.603		4.256[c]
isoheptane	3.093	3.118	3.574	2.452	2.343	4.008	3.957	4.410	2.693	2.724	3.292		
neoheptane	0.145	0.105	0.125		0.113	0.232	0.225	0.288		0.091	0.176		
n-octane	4.091	4.436	5.451	2.946	2.720	6.186	6.346	4.091	3.552	4.091	4.559		
isooctane	1.994	2.055	2.111	1.943	1.910	2.196	2.313	2.313	1.980	1.981	2.038		

[a] B2K-PLYP and B2GP-PLYP results at PW6B95/6-311G(d,p) geometries. Geometries are fully optimized at remaining levels of theory for butane, pentane, hexane, and neoheptane, but PW6B95/6-311G(d,p) reference geometries are used for remaining heptanes and octanes. CCSD(T) results at MP2/cc-pVTZ geometries, using the AVQZ basis set for *n*-butane, the AVTZ basis set for *n*-pentane, and the PVTZ basis set for *n*-hexane. [b] SCF and CCSD energies extrapolated from the cc-pV{T,Q}Z basis set pair and the (T) contribution extrapolated from the cc-pV{D,T}Z basis set pair. [c] MP2:CC result.

type structure is just 0.5 kcal/mol above, and a third, syn-like conformer, is found 3.3 kcal/mol above the global minimum.

3-Methylpentane has six conformers. The global minimum has C_s symmetry; the other ones are best understood by considering *n*-pentane with a substituent in the 3 position, making the 4-fold degenerate TG and GX^- conformer split up into nonequivalent pairs.

Biisopropyl (2,3-dimethylbutane) has just two conformers, the trans conformer with C_{2h} symmetry and, less than 0.1 kcal/mol higher, the gauche conformer with C_2 symmetry.

Neoheptane has just three, the global minimum with C_s symmetry and two asymmetric conformers at 2.3 and 2.7 kcal/mol higher. Their impact on the thermodynamic functions is minimal.

D. Thermodynamic Function Corrections. As pointed out in the Introduction, one of the main motivations for the present study was a thermochemical one, namely, the need for reliable conformer corrections to the enthalpy function and Gibbs energy function of the alkanes. Such data for the various species considered in this paper, as well as in ref 41, can be found in Table 6 for various levels of theory.

As can be seen there, for the few systems where extended basis set CCSD(T) data are available, B2K-PLYP-D/pc-2 yields nearly identical results. We thus take this level as our yardstick for the thermodynamic function corrections for the remaining species.

The enthalpy function correction, which is what is needed for obtaining heats of formation from atomization energies, or vice versa, exhibits fairly mild sensitivity to the level of theory. Broadly speaking, the M06 family tends to significantly underestimate the corrections, while popular functionals like B3LYP tend to overestimate it. The anomalous negative sign for M06 and M06-L in the case of diisopropyl results from the wrong conformer ordering being predicted.

The sensitivity of the Gibbs energy function is rather more pronounced, and the behavior of the different functionals is rather less systematic.

We finally address the issue of cross-coupling with zero-point and thermal corrections. Table 7 compares B2K-PLYP-D/pc-2 thermal conformer corrections obtained in three different manners, (a) using bottom-of-the-well conformer energy differences (ΔE_e); (b) using conformer energy differences at 0 K (ΔE_0); and (c) including individual rovibrational partition functions for all conformers (i.e., not assuming the rovibrational and conformer partition functions to be factorizable). For want of a computationally affordable alternative, the RRHO (rigid rotor−harmonic oscillator) approximation was applied to both ZPVE and thermal corrections. (The molecular constants required were obtained at the PW6B95/6-311G** level with "ultrafine" integration grids, that is, pruned (99, 590) for energy and gradient and (50, 194) for harmonic frequencies. For more on the sensitivity of harmonic frequencies to DFT integration grids, see ref 51.) The thermochemical consequences of the RRHO approximation on the relative conformer energies are hard to quantify. The effects of (b) and (c) on the enthalpy function are generally quite modest for the *n*-alkanes (relatively speaking) but more pronounced for some of the branched alkanes, notably 3-methylpentane, isoheptane, and isooctane. These general tendencies are exacerbated for the Gibbs energy function.

For *n*-butane through *n*-heptane, we considered internal rotation corrections for each individual conformer by means of the Ayala−Schlegel approximation.[52] These results are given in the bottom pane of Table 7. As can be seen there, the effect on the enthalpy functions is minimal, and that on the Gibbs energy function is quite modest as well, considering that 0.1 eu translates to less than 0.03 kcal/mol in the free energy. We thus feel justified in not considering it for the other conformers.

TABLE 7: B2K-PLYP-D(0.22)/pc-2//PW6B95/6-311G(d,p) Thermal Conformer Corrections at 298.15 K Using Three Approximations, (a) Using "Bottom of the Well" Conformer Energy Differences; (b) Using the Same at 0 K; and (c) Accounting for Individual Rovibrational Partition Functions

	gef(T) in e.u.			$H_{298} - H_0$ in kcal/mol		
	just ΔE_e	just ΔE_0	vib. avg.	just ΔE_e	just ΔE_0	vib. avg.
n-butane	1.053	1.067	1.149	0.256	0.255	0.267
n-pentane	2.090	1.748	2.539	0.468	0.489	0.508
n-hexane	3.166	2.651	3.419	0.678	0.718	0.682
n-heptane	4.284	3.632	4.628	0.886	0.934	0.826
n-octane	5.466	4.528	5.301	1.081	1.193	1.025
3-methylpentane	3.004	2.632	2.429	0.265	0.324	0.229
diisopropyl	2.043	2.088	1.981	0.041	0.028	0.031
isoheptane	3.573	3.086	2.761	0.456	0.516	0.401
isohexane	2.466	2.149	1.893	0.243	0.271	0.173
isooctane	2.111	2.000	1.849	0.156	0.165	0.122
isopentane	1.625	1.568	1.568	0.092	0.087	0.084
neoheptane	0.125	0.075	0.027	0.147	0.100	0.033
Linear Regression for *n*-Alkanes (# of backbone torsions)						
slope	1.102	0.881	1.039	0.207	0.232	0.183
intercept	−0.094	0.083	0.289	0.053	0.021	0.111
R^2	0.9993	0.9964	0.9882	0.9998	0.9993	0.9928
With Individual Internal Rotation Corrections for Each Conformer						
n-butane	1.030	1.043	1.125	0.259	0.257	0.270
n-pentane	2.138	1.778	2.557	0.466	0.493	0.508
n-hexane	3.246	2.704	3.458	0.672	0.723	0.682
n-heptane	4.408	3.716	4.686	0.873	0.939	0.824

Finally, one wonders about whether a CH_2 group equivalent could be applied to longer alkane chains. Linear regression of the corrections for *n*-butane through *n*-octane in terms of the number of backbone torsion angles reveals especially good correlation coefficients at the bottom of the well ($R^2 = 0.9998$ for $H_{298} - H_0$ and 0.9993 for gef(T)). If the zero-point energy is taken into account, we see a mild deterioration of the fit for $H_{298} - H_0$ but a somewhat more pronounced one for gef(T), while the fits including full thermal averaging become a bit noisier than desirable but still adequate for estimation purposes.

IV. Conclusions

Conformational energies of *n*-butane, *n*-pentane, and *n*-hexane have been calculated at the CCSD(T) level and at or near the basis set limit. Post-CCSD(T) contributions were considered and found to be unimportant. The data thus obtained were used to assess the performance of a variety of density functional methods. Double-hybrid functionals like B2GP-PLYP and B2K-PLYP, especially with a small Grimme-type empirical dispersion correction, are capable of rendering conformational energies of CCSD(T) quality. These were then used as a secondary standard for a larger sample of alkanes, including isopentane and the branched hexanes as well as key isomers of heptane and octane. Popular DFT functionals like B3LYP, B3PW91, BLYP, PBE, and PBE0 tend to overestimate conformer energies without dispersion correction, while the M06 family severely underestimates GG interaction energies. Grimme-type dispersion corrections for these overcorrect and lead to qualitatively wrong conformer orderings. All of these functionals also exhibit deficiencies in the conformer geometries, particularly the backbone torsion angles. The PW6B95 and, to a lesser extent, BMK functionals are relatively free of these deficiencies.

The performance of these methods is further investigated to derive conformer ensemble corrections to the enthalpy function, $H_{298} - H_0$, and the Gibbs energy function, $\mathrm{gef}(T) \equiv -[G(T) - H_0]/T$, of these alkanes. These are essential for accurate computed heats of formation of especially the larger species as the corrections for these are several times the expected uncertainty in modern computational thermochemistry methods such as W4 theory. While $H_{298} - H_0$ is only moderately sensitive to the level of theory, gef(T) exhibits more pronounced sensitivity. Once again, double hybrids acquit themselves very well.

The effects of the zero-point energy and of nonfactorizable rovibrational partition functions were considered and found to be smaller than those arising from an inadequate level of theory for the conformer energies.

Acknowledgment. Research at Weizmann was funded by the Israel Science Foundation (Grant 709/05), the Helen and Martin Kimmel Center for Molecular Design, and the Weizmann Alternative Energy Research Initiative (AERI). J.M.L.M. is the incumbent of the Baroness Thatcher Professorial Chair of Chemistry and a member ad personam of the Lise Meitner-Minerva Center for Computational Quantum Chemistry.

Supporting Information Available: Optimized geometries in Cartesian coordinates of all conformers discussed here, as well as visualization of same using Jmol. PW6B95/6-311G** harmonic frequencies, zero-point vibrational energies, and vibrational enthalpy functions of all conformers and Table S-1 containing relative energies, point groups, and degeneracies. This material is available free of charge via the Internet at http://pubs.acs.org.

Note Added in Proof. After ref 41 was published, we discovered that the low-frequency vibrations of tetrahedrally symmetric neopentane exhibit a grid hypersensitivity issue.[53] Recalculating the vibrational frequencies of all species in ref 41 and Table 1 of the present work with an "ultrafine" pruned (99,590) integration grid for energy and gradient, and a "medium" (75,194) grid for solution of the CPKS equations, affects the enthalpy function of neopentane by +0.17 kcal/mol, of hexamethylethane by +0.05 kcal/mol, and of the remaining species by 0.02 kcal/mol or less. The heat content function of neopentane is thus raised to 5.01 kcal/mol. Incidentally, when the reference geometry is not properly symmetrized, the hypersensitivity disappears. We thank Will Stevens and Prof. Tomas Baer (UNC, Chapel Hill) for helpful correspondence. In addition, we considered the *n*-pentane and *n*-hexane conformer energies with the B97-D functional,[54] in which the B97-1 exchange-correlation functional[55] was refitted in the presence of a dispersion correction with $s_6 = 1.25$. While B97-D suffers from the same overcorrection problem discussed in the paper, the ordering of the *n*-hexane conformers is predicted correctly, unlike for the original B97-1 functional with an a posteriori dispersion correction ($s_6 = 0.65^{41}$) added.

References and Notes

(1) Pitzer, K. S. *J. Chem. Phys.* **1940**, *8*, 711.

(2) Smith, G. D.; Jaffe, R. L. *J. Phys. Chem.* **1996**, *100*, 18718.

(3) Allinger, N. L.; Fermann, J. T.; Allen, W. D.; Schaefer, H. F., III. *J. Chem. Phys.* **1997**, *106*, 5143.

(4) Salam, A.; Deleuze, M. S. *J. Chem. Phys.* **2002**, *116*, 1296.

(5) Karton, A.; Rabinovich, E.; Martin, J. M. L.; Ruscic, B. *J. Chem. Phys.* **2006**, *125*, 144108.

(6) Karton, A.; Martin, J. M. L.; Taylor, P. R. *J. Chem. Phys.* **2007**, *127*, 064104.

(7) Tajti, A.; Szalay, P. G.; Császár, A. G.; Kalláy, M.; Gauss, J.; Valeev, E. F.; Flowers, B. A.; Vázquez, J.; Stanton, J. F. *J. Chem. Phys.* **2004**, *121*, 11599.

(8) Bomble, Y. J.; Vázquez, J.; Kállay, M.; Michauk, C.; Szalay, P. G.; Császár, A. G.; Gauss, J.; Stanton, J. F. *J. Chem. Phys.* **2006**, *125*, 064108.

(9) Harding, M. E.; Vázquez, J.; Ruscic, B.; Wilson, A. K.; Gauss, J.; Stanton, J. F. *J. Chem. Phys.* **2008**, *128*, 114111.

(10) Herrebout, W. A.; van der Veken, B. J.; Wang, A.; Durig, J. R. *J. Phys. Chem.* **1995**, *99*, 578.

(11) East, A. L. L.; Allen, W. D.; Császár, A. G. In *Structure and Conformations of Non-Rigid Molecules*; Laane, J., Dakkouri, M., van der Veken, B., Oberhammer, H., Eds.; Kluwer: Dordrecht, The Netherlands, 1993; pp 343−373.

(12) Császár, A. G.; Allen, W. D.; Schaefer, H. F., III. *J. Chem. Phys.* **1998**, *108*, 9751.

(13) Balabin, R. M. *J. Phys. Chem. A* **2009**, *113*, 1012.

(14) (a) Tsuzuki, S.; Schäfer, L.; Goto, H.; Jemmis, E. D.; Hosoya, H.; Siam, K.; Tanabe, K.; Osawa, E. *J. Am. Chem. Soc.* **1991**, *113*, 4665. (b) Goto, H.; Osawa, E.; Yamato, M. *Tetrahedron* **1993**, *49*, 387.

(15) Tasi, G.; Mizukami, F.; Pálinkó, I.; Csontos, J.; Györffy, W.; Nair, P.; Maeda, K.; Toba, M.; Niwa, S.; Kiyozumi, Y.; Kiricsi, I. *J. Phys. Chem. A* **1998**, *102*, 7698.

(16) Tasi, G.; Mizukami, F.; Csontos, J.; Györffy, W.; Pálinkó, I. *J. Math. Chem.* **2000**, *27*, 191.

(17) Grimme, S. *J. Chem. Phys.* **2006**, *124*, 034108.

(18) Karton, A.; Tarnopolsky, A.; Lamère, J.-F.; Schatz, G. C.; Martin, J. M. L. *J. Phys. Chem. A* **2008**, *112*, 12868.

(19) *MOLPRO*, version 2008.1, a package of ab initio programs; Werner, H.-J.; Knowles, P. J.; Lindh, R.; Manby, F. R.; Schütz, M.; Celani, P.; Korona, T.; Mitrushenkov, A.; Rauhut, G.; Adler, T. B.; Amos, R. D.; Bernhardsson, A.; Berning, A.; Cooper, D. L.; Deegan, M. J. O.; Dobbyn, A. J.; Eckert, F.; Goll, E.; Hampel, C.; Hetzer, G.; Hrenar, T.; Knizia, G.; Köppl, C.; Liu, Y.; Lloyd, A. W.; Mata, R. A.; May, A. J.; McNicholas, S. J.; Meyer, W.; Mura, M. E.; Nicklass, A.; Palmieri, P.; Pflüger, K.; Pitzer, R.; Reiher, M.; Schumann, U.; Stoll, H.; Stone, A. J.; Tarroni, R.; Thorsteinsson, T.; Wang, M.; Wolf, A. http://www.molpro.net (2008).

(20) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. *Gaussian 03*, revision E.01; Gaussian, Inc.: Wallingford, CT, 2004.

(21) (a) *MRCC*, a string-based general coupled cluster program suite; Kállay, M. (b) Kállay, M.; Surján, P. R. *J. Chem. Phys.* **2001**, *115*, 2945. (c) MRCC Homepage; http://www.mrcc.hu (2008).

(22) Perdew, J. P.; Schmidt, K. *AIP Conf. Proc.* **2001**, *577*, 1.

(23) Becke, A. D. *Phys. Rev. A* **1988**, *38*, 3098.

(24) Lee, C.; Yang, W.; Parr, R. G. *Phys. Rev. B* **1988**, *37*, 785.

(25) (a) Perdew, J. P.; Burke, K.; Ernzerhof, M. *Phys. Rev. Lett.* **1996**, *77*, 3865. (b) Perdew, J. P.; Burke, K.; Ernzerhof, M. *Phys. Rev. Lett.* **1997**, *78*, 1396; Erratum.

(26) Zhao, Y.; Truhlar, D. G. *J. Chem. Phys.* **2006**, *125*, 194101.

(27) Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648.

(28) Stephens, P. J.; Devlin, F. J.; Chabalowski, C. F.; Frisch, M. J. *J. Phys. Chem.* **1994**, *98*, 11623.

(29) Perdew, J. P.; Chevary, J. A.; Vosko, S. H.; Jackson, K. A.; Pederson, M. R.; Singh, D. J.; Fiolhais, C. *Phys. Rev. B* **1992**, *46*, 6671.

(30) Adamo, C.; Barone, V. *J. Chem. Phys.* **1999**, *110*, 6158.

(31) Becke, A. D. *J. Chem. Phys.* **1996**, *104*, 1040.

(32) Zhao, Y.; Truhlar, D. G. *J. Phys. Chem. A* **2005**, *109*, 5656.

(33) Boese, A. D.; Martin, J. M. L. *J. Chem. Phys.* **2004**, *121*, 3405.

(34) (a) Zhao, Y.; Truhlar, D. G. *Theor. Chem. Acc.* **2007**, *120*, 215. (b) Zhao, Y.; Truhlar, D. G. *Acc. Chem. Res.* **2008**, *41*, 157.

(35) Tarnopolsky, A.; Karton, A.; Sertchook, R.; Vuzman, D.; Martin, J. M. L. *J. Phys. Chem. A* **2008**, *112*, 3.

(36) Dunning, T. H. *J. Chem. Phys.* **1989**, *90*, 1007.

(37) Kendall, R. A.; Dunning, T. H.; Harrison, R. J. *J. Chem. Phys.* **1992**, *96*, 6796.

(38) (a) Jensen, F. *J. Chem. Phys.* **2001**, *115*, 9113. Jensen, F. *J. Chem. Phys.* **2002**, *116*, 3502; Erratum.

(39) Grimme, S. *J. Comput. Chem.* **2007**, *27*, 1787.

(40) Schwabe, T.; Grimme, S. *Phys. Chem. Chem. Phys.* **2007**, *9*, 3397.

(41) Karton, A.; Gruzman, D.; Martin, J. M. L. *J. Phys. Chem. A* **2009**, *113*, 8434.

(42) Jurecka, P.; Sponer, J.; Cerny, J.; Hobza, P. *Phys. Chem. Chem. Phys.* **2006**, *8*, 1985.

(43) Balabin, R. M. *J. Chem. Phys.* **2008**, *129*, 164101.

(44) Pitzer, K. S.; Brewer, L. *Thermodynamics*; McGraw-Hill: New York, 1961; Chapter 27.

(45) Martin, J. M. L.; François, J. P.; Gijbels, R. *J. Chem. Phys.* **1992**, *97*, 3530.

(46) (a) Martin, J. M. L.; de Oliveira, G. *J. Chem. Phys.* **1999**, *111*, 1843. (b) Martin, J. M. L.; Parthiban, S. *J. Chem. Phys.* **2001**, *114*, 6014. (c) Martin, J. M. L.; Parthiban, S. In *Quantum-Mechanical Prediction of Thermochemical Data*; Cioslowski, J., Ed.; Understanding Chemical Reactivity; Kluwer: Dordrecht, The Netherlands, 2001; Vol. 22.

(47) Klauda, J. B.; Brooks, B. R.; MacKerell, A. D.; Venable, R. M.; Pastor, R. W. *J. Phys. Chem. B* **2005**, *109*, 5300.

(48) (a) Grimme, S. *J. Chem. Phys.* **2003**, *118*, 9095. (b) For a physical interpretation of the SCS-MP2 method in terms of Feenberg scaling, see: Szabados, A. *J. Chem. Phys.* **2006**, *125*, 214105.

(49) NIST Computational Chemistry Comparison and Benchmark Database, NIST Standard Reference Database Number 101, Release 12; Johnson, R. D., III., Ed.; NIST: Gaithersburg, MD, http://srdata.nist.gov/cccbdb (Aug 2005).

(50) Grimme, S.; Mück-Lichtenfeld, C. *Chirality* **2008**, *20*, 1009.

(51) Martin, J. M. L.; Bauschlicher, C. W.; Ricca, A. *Comput. Phys. Commun.* **2001**, *133*, 189.

(52) Ayala, P. Y.; Schlegel, H. B. *J. Chem. Phys.* **1998**, *108*, 2314.

(53) Martin, J. M. L.; Bauschlicher, C. W.; Ricca, A. *Comput. Phys. Commun.* **2001**, *133*, 189.

(54) Grimme, S. J. *Comput. Chem.* **2006**, *27*, 1787.

(55) Hamprecht, F. A.; Cohen, A. J.; Tozer, D. J.; Handy, N. C. *J. Chem. Phys.* **1998**, *109*, 6264.

JP903640H