JOC The Journal of Organic Chemistry

ARTICLE

pubs.acs.org/joc

# On the Advantages of Hydrocarbon Radical Stabilization Energies Based on R—H Bond Dissociation Energies

Matthew D. Wodrich,[†] W. Chad McKee,[‡] and Paul von Ragué Schleyer*[,‡]

[†]School of Chemistry and Biochemistry, Université de Genève, 30 quai Ernest-Ansermet, CH-1211 Genève 4, Switzerland

[‡]Department of Chemistry and Center for Computational Chemistry, University of Georgia, Athens, Georgia 30602, United States

S Supporting Information

**ABSTRACT:** Hydrocarbon radical stabilization energy (RSE) estimates based on the differences in R—H vs $CH_3$—H bond dissociation energies have inherent advantages over RSEs based on R—$CH_3$ vs $CH_3$—$CH_3$, as well as R—R vs $CH_3$—$CH_3$ comparisons, since the R—$CH_3$ and R—R reference systems are prone to unbalanced contaminating intramolecular interactions involving the R groups. When the effects of steric crowding, branching, protobranching, conjugation, and hyperconjugation are taken into account, R—$CH_3$ and R—R based RSE values are nearly identical to R—H RSEs. Corrections for electronegativity differences between H and R are not needed to achieve agreement.

**Should radical stabilization energies (RSE vs. $CH_3$, kcal/mol) be based on bond dissociation energies (BDE) of C-H or C-C bonds?**

| R•= | $1^o$ | $2^o$ | $3^o$ |
|---|---|---|---|
| $RSE_{CH}$[R•] = BDE[$CH_3$-H] - BDE[R-H] | 3.9 | 6.4 | 8.3 |
| $RSE_{CC}$[R•] = 1/2 (BDE[$CH_3$-$CH_3$] - BDE[R-R]*) | 1.1 | 1.4 | 3.7 |

* corrected for strain

## INTRODUCTION

The radical stabilization energies (RSEs) of carbon-based hydrocarbon radicals are based typically on quantitative comparisons with the smallest possible alkyl radical reference standard, $CH_3$•, since complicating effects are minimized. But opinions are diverse and the literature is extensive.[1−26] Ideally, RSEs should be intrinsic quantities associated only with the species themselves, although their detailed interpretation may be quite complex. Thus, even $CH_3$• can be stabilized in the absolute sense, e.g., by conjugative geminal HCH interactions[27] and by spin polarization, which is responsible for its hyperfine ESR coupling.[28] The intrinsic stabilization energy of a radical may be defined by comparing its real energy with that of its hypothetical model, which lacks all stabilizing effects. In essence, the same species (when rendered interaction-free) serves as a model for itself. This definition follows the Pauling—Wheland concept of resonance energy, which is based on the comparison of the energy of a real molecule with that of its most stable (hypothetical) resonance contributor at the same geometry.[29] The intrinsic stabilization of radicals is discussed further in the last section of this paper.

However, literature RSE estimates are relative rather than inherent values and depend not only on the choice of a comparison standard (e.g., $CH_3$•) but also on the defining equation, which involves the selection of additional reference molecules. Clearly such empirical RSEs should be completely independent of the method used for their determination or evaluation, but each method introduces interpretive problems, which need to be considered or eliminated in order to achieve consistency. Thus, RSE values based on bond dissociation energy (BDE) comparisons often depend on extraneous interactions present in the radical precursors but not in the product radicals. Since these "contaminations" are at a minimum in $CH_3$• and $CH_4$, the BDE of the $CH_3$—H dissociation appears to be the logical choice as the reference standard for carbon-centered radicals. Nevertheless, other definitions of RSEs have been proposed and, as illustrated by the titles of recent papers published in this journal, this topic has become increasingly controversial:

"Choice of Bond Dissociation Enthalpies on Which To Base the Stabilization Energies of Simple Radicals: DH(R—H) Is Preferred Because DH(R—Me) and DH(R—R) Are Perturbed by Changes in Chain Branching" by Poutsma.[25]

"Shortcomings of Basing Radical Stabilization Energies on Bond Dissociation Energies of Alkyl Groups to Hydrogen" by Zavitsas, Rogers, and Matsunaga (ZRM).[1]

The present paper supports Poutsma[25] by emphasizing the inherent advantages of hydrocarbon RSEs based on R—H bond dissociation energies. We take issue with ZRM's conclusion that $SE_H$ RSEs (i.e., RSEs derived from R—H vs $CH_3$—H BDE comparisons) "do not provide a quantitative measure of radical stabilization energies."[1] We show that alternative RSE estimates derived from R—$CH_3$ vs $CH_3$—$CH_3$ and R—R vs $CH_3$—$CH_3$ BDE comparisons (referred to as $SE_{CH_3}$ and $SE_{R-R}$, respectively) are equivalent to $SE_H$ RSEs, provided that the necessary corrections for interactions involving the R groups in R—$CH_3$ and R—R are taken into account. Furthermore, we show how such corrections overcome ZRM's recent criticism that "$SE_H$ stabilization energies are not transferable and cannot be used to estimate carbon—carbon BDE[R—R′] or symmetrical BDE[R—R]" values.[1]

## RESULTS AND DISCUSSION

"Bond dissociation energies" are defined as the change in energy upon homolytic cleavage of, e.g., R—X bonds into two

**Received:** August 23, 2010
**Published:** March 18, 2011

**Table 1. Selected Radical Stabilization Energies (in kcal/mol vs $CH_3$•) for the $SE_H$, $SE_{CH_3}$, $SE_{R-R}$, and $SE_Z$ Schemes**[a]

| radical | $SE_H$ RSE eq 1 | $SE_{CH_3}$ RSE eq 2 | $SE_{R-R}$ RSE eq 3a | $SE_Z$ RSE eq 3b |
|---|---|---|---|---|
| $CH_3$• | 0.00 | 0.00 | 0.00 | 0.00 |
| 1° ($C_2H_5$•) | 3.91 | 1.22 | 1.17 | 1.1 |
| 2° ($i$-$C_3H_7$•) | 6.37 | 1.37 | 2.58 | 1.4 |
| 3° ($t$-$C_4H_9$•) | 8.32 | 2.71 | 5.77 | 3.7 |
| benzyl | 15.13 | 12.55 | 11.60 | 11.7 |
| allyl | 16.73 | 14.15 | 14.43 | 14.3 |
| vinyl | −6.05 | −11.61 | −13.31 | −11.6 |
| phenyl | −7.79 | −13.41 | −13.65 | −13.1 |

[a] $SE_H$, $SE_{CH_3}$, and $SE_{R-R}$ RSEs are computed from eqs 1, 2 and 3a, respectively, using experimental heats of formation at 298 K from ref 42. $SE_Z$ values are taken from ref 1 and are derived from eq 3b, where the "strain/stabilization free" BDE[R−R] values were obtained separately by ZRM from Pauling's equation (eq 4, see ref 1 for discussion).

radicals, R• and X•.[3−15,26] When X is constant, the relative BDEs for a series of related RX compounds can be used to evaluate a scale of radical stabilization energies of R•. We stress that, "bond energies" and "bond dissociation energies" are quite different.[2] "Bond energies" (BEs) are based on the total atomization energies (AEs, i.e., dissociation of all the Lewis electron pair bonds) of molecules. The AE of a molecule is taken to be the sum of all of the BEs. In contrast, "bond dissociation energies" involve the dissociation of only one bond in a molecule and the relaxation of the radical fragments formed. Not only are, e.g., the A and B moieties in A−B quite different from the separated A• and B• radical fragments, but also the intramolecular interactions between A and B in A−B have nothing to do with the inherent stabilization of the A• and B• radicals individually. Thus, the C−H *bond energy* (BE, in kcal/mol) evaluations of Exner and Schleyer[2] (103.9 methane, 104.1 ethane, 104.3 propane $CH_2$, 104.4 iso-butane CH, showed *essentially no variation in this basic alkane set*, in contrast to the well-known decrease in the corresponding BDEs.[26,30] The BE of the tertiary C−H bond in iso-butane itself is not weakened. The smaller BDE of this bond is largely due to the stabilization of the *tert*-butyl radical by effects that influence the CH bond energy of the parent hydrocarbon to a much smaller extent, if at all.[2]

Ideally, empirical RSE values based on R−X BSEs should be independent of X and free from any extraneous effects of X in the R−X precursors. Obviously this requirement results in difficulties in evaluating RSEs in practice; all commonly employed methods of determination have conceptual flaws and discernible imperfections. Pople's methyl stabilization energies (MSEs),[18] based on R = $CH_3$ and X = H (the smallest possible and least complicating X atom or group), are the most widely used RSE scale.[19−24] These MSEs (or $SE_H$ values as termed here) are defined by eq 1 as the difference between the BDE of methane [$CH_3$−H] and that of the R−H bond of interest, where R• is a carbon-centered radical.

$$SE_H[R\bullet] = BDE[CH_3 - H] - BDE[R - H] \qquad (1)$$

However, it is now well-known that substituting H in eq 1 with, for example, a methyl group (eq 2) yields markedly different alkyl RSE values (cf., the $SE_{CH_3}$ and $SE_H$ RSEs in Table 1).[16,25,30,31] Moreover, as ZRM stress, relative RSEs based on R−X BDEs also depend strongly on the electronegativity of X, and approaches employing electronegativity corrections are widely applicable for BDE estimations.[16] Although different methods of deriving alkyl RSEs often predict qualitatively similar relative radical stabilities,[32,33] the choice of the optimum reference standard used to define the scale of quantitative RSEs remains controversial, as is well illustrated by the issues raised in the two disputing papers[1,25] we discuss here.

$$SE_{CH_3}[R\bullet] = BDE[CH_3{-}CH_3] - BDE[R{-}CH_3] \qquad (2)$$

$$SE_{R-R}[R\bullet] = \frac{1}{2}(BDE[CH_3{-}CH_3] - BDE[R - R]) \qquad (3a)$$

$$SE_Z[R\bullet] = \frac{1}{2}BDE[CH_3{-}CH_3] - BDE[R - R]^*) \qquad (3b)$$

*BDE[R−R] is corrected for strain/stabilizing effects present in R−R by ZRM as described in ref 1; when no such effects are present eqs 3a and 3b are equivalent.

$$D[A - B] = \frac{1}{2}(D[A - A] + D[B - B]) + 23(\Delta\chi)^2 \qquad (4)$$

Despite Poutsma's support for the conceptual and numerical advantages of eq 1 for defining alkyl RSEs,[25] ZRM disparaged the use of methane as the reference choice.[1] Instead, they favored $SE_Z$ values for alkyl radicals given by an alternative approach (eq 3b) based on the BDEs of symmetrical radical precursors, R−R.[16] The purported advantage is the elimination of errors due to the electronegativity difference between C and H inherent in MSE evaluations (eq 1). This concern originates from Pauling's electronegativity definition (eq 4),[34,35] based on the differences ($\Delta\chi$) between the average of homolytic [(AA + BB)/2] and heterolytic (AB) bond dissociation enthalpies. The importance of *large*, well established, $\Delta\chi$ differences has been demonstrated by Zavitsas et al. in related work,[16] and this issue is not in dispute here. However, $\Delta\chi$ differences between C and H are *small*, considering the "relatively nonpolar nature of the R−H bond",[25] and the many electronegativity values for C and H that have been determined[36] often differ only minimally, if at all.[37] This conclusion is supported by Quack et al.'s analysis of the high resolution vibrational spectra of the methane H,D isotopomers, which "firmly established" the $C^-H^+$ direction of the polarity of the CH bond dipole moment expected from electronegativity and determined its value ((6.1 ± 1.0) × $10^{-3}$ D)[38,39] to be much smaller than Pauling's choice of 0.4 D, based on his electronegativity difference between C and H.[35] Thus, significant contamination of $SE_H$ RSEs due to such differences appears doubtful.

Furthermore, any errors arising from electronegativity differences between C and H should largely balance along a series of related substrates; *corrections for RSE evaluations would not be significant from one RH to the next unless differences* ($\Delta\chi$) *exist in the electronegativities of the different R groups*. However, on the basis of their own derivations of $\chi$ values, ZRM argue that $\Delta\chi$ corrections for different R groups "cannot be neglected," since, for example, they constitute "30% of the $SE_H$ value of 6.5 kcal/mol for isopropyl" and "similar percentages are obtained with 1° and 3° R•." Yet, many literature evaluations of the electronegativities of methyl, primary, secondary, and tertiary alkyl groups using various methods find *nearly the same* $\chi$ *values for all of these groups*. Huheey's classical assessment of group electronegativities gave methyl, 2.27; ethyl, 2.28; isopropyl, 2.28; and *tert*-butyl, 2.28, nearly identical with the Clifford-Jaffé values.[40] Eight additional complete sets of all four alkyl group $\chi$ values (including ZRM's) are summarized in Table 4 of Cao and Luo's recent paper.[41] In five of the eight sets, the $\chi$ of the *tert*-butyl group actually is slightly *larger* than $\chi$ for methyl; just the opposite of the 2003 assessment of the ZRM authors.[16] Thus, there is no firm basis for expecting R−H electronegativity differences for various R's (if any exist at all) to be significant energetically in RSE evaluations based on methane as in eq 1. We note that $\Delta\chi$ corrections, if any be required, are very much smaller than other necessary but unconsidered corrections for imbalances neglected in the ZRM treatment.[1]

What then is responsible for the divergence in the stabilization energies given by eqs 1, 2, 3a, and 3b (see Table 1)? As Poutsma pointed out,[25] R−R′ molecules have steric and other unbalanced interactions between the R and R′ moieties that are not involved in stabilizing the R• and R′• radicals. Obviously, such interactions between R and R′ in R−R′ are not present in the separated R• and R′• radicals or when R−H and R′−H are individual molecules. After energies associated with the loss of steric, topological, conjugative, and hyperconjugative interactions in R−R′ are properly accounted for, the corrected $SE_{CH_3}$ and $SE_{R-R}$ RSE estimates match those predicted by the $SE_H$ method closely.

Ethyl radical RSE evaluations are illustrative. $SE_H$ employs ethane and methane as reference compounds (eq 5), $SE_{R-R}$ utilizes ethane and *n*-butane (the symmetrical precursor of the ethyl radical) (eq 6), and the $SE_{CH_3}$ method uses ethane and propane (eq 7). Although eqs 5−7 give different values, the required simple protobranching correction (2.69 kcal/mol, eq 8) to eqs 6[43] and 7 eliminates the discrepancy.

$$\begin{gathered}\mathrm{CH_3CH_2\bullet + CH_4 \rightarrow CH_3CH_3 + CH_3\bullet}\\ \mathrm{SE_H(Et\bullet) = 3.91\ kcal/mol}\end{gathered}\tag{5}$$

$$\begin{gathered}\frac{1}{2}\mathrm{C_2H_6 + CH_3CH_2\bullet} \rightarrow \frac{1}{2}\ n\text{-}\mathrm{C_4H_{10} + CH_3\bullet}\\ \mathrm{SE_{R-R}(Et\bullet) = 1.17\ kcal/mol}\end{gathered}\tag{6}$$

$$\begin{gathered}\mathrm{CH_3CH_2\bullet + CH_3CH_3 \rightarrow CH_3CH_2CH_3 + CH_3\bullet}\\ \mathrm{SE_{CH_3}(Et\bullet) = 1.22\ kcal/mol}\end{gathered}\tag{7}$$

$$\mathrm{CH_3CH_2CH_3 + CH_4 \rightarrow 2CH_3CH_3 = 2.69\ kcal/mol}\tag{8}$$

Poutsma pointed out the readily apparent conceptual flaw of eq 7,[25] which also is present in eq 6: the protobranching interactions in the alkane reference molecules are not balanced. While eqs 5−7 compare the methyl and ethyl radicals (and include the hyperconjugative stabilization energy of $CH_3CH_2\bullet$), the propane product of eq 7 and the 1/2 *n*-butane product of eq 6 are stabilized by a protobranching interaction, which is unbalanced on the reactant sides.[25,29,44−51] This imperfection is not present in eq 5. As noted by Poutsma,[25] subtracting eq 5 from eq 7 gives eq 8, which evaluates the stabilization due to a single protobranch.[29,44−53]

As both propane and *n*-Pr• have a single protobranch, a correction is not needed in eq 9. Not surprisingly, the $SE_H$ values of eq 5 (3.91 kcal/mol) for Et• and protobranching-balanced eq 9 (3.78 kcal/mol) for *n*-Pr• are nearly identical; both evaluate the RSEs of primary alkyl radicals properly. In contrast, the $SE_{CH_3}$ and $SE_{R-R}$ methods fail for the *n*-Pr• RSE and give values (Table 1) that are too low (unless corrected for their protobranching and strain imbalances).

$$\begin{gathered}\mathrm{CH_3CH_2CH_2\bullet + CH_4 \rightarrow CH_3CH_2CH_3 + CH_3\bullet}\\ \mathrm{SE_H}(n\text{-}\mathrm{Pr\bullet}) = 3.78\ \mathrm{kcal/mol}\end{gathered}\tag{9}$$

Corrections for protobranching imbalances in the $SE_{CH_3}$ evaluation of secondary and tertiary alkyl RSEs also result in values nearly identical to those derived from the $SE_H$ method. However, applying the $SE_{R-R}$ approach to estimate these quantities introduces additional problems. For example, compare the *tert*-butyl radical RSEs (kcal/mol) given by the $SE_H$ (8.32), $SE_{R-R}$ (5.77), and $SE_{CH_3}$ (2.71) methods (eqs 10, 11, and 12, respectively, based on experimental heats of formation).

$$\begin{gathered}i\text{-}\mathrm{C_4H_9\bullet + CH_4} \rightarrow i\text{-}\mathrm{C_4H_{10} + CH_3\bullet}\\ \mathrm{SE_H}(t\text{-}\mathrm{Bu\bullet}) = 8.32\ \mathrm{kcal/mol}\end{gathered}\tag{10}$$

$$\begin{gathered}i\text{-}\mathrm{C_4H_9\bullet} + \frac{1}{2}\mathrm{C_2H_6} \rightarrow \frac{1}{2}\,\text{hexamethylethane} + \mathrm{CH_3\bullet}\\ \mathrm{SE_{R-R}}(t\text{-}\mathrm{Bu\bullet}) = 5.77\ \mathrm{kcal/mol}\end{gathered}\tag{11}$$

$$\text{corrected (see text) }\mathrm{SE_{R-R}}(t\text{-}\mathrm{Bu\bullet}) = 8.34\mathrm{kcal/mol}\tag{11corr}$$

$$\begin{gathered}i\text{-}\mathrm{C_4H_9\bullet + CH_3CH_3} \rightarrow neo\text{-}\mathrm{C_5H_{12} + CH_2\bullet}\\ \mathrm{SE_{CH_3}}(t\text{-}\mathrm{Bu\bullet}) = 2.71\ \mathrm{kcal/mol}\end{gathered}\tag{12}$$

$$\text{corrected (see text) }\mathrm{SE_{CH_3}}(t\text{-}\mathrm{Bu\bullet}) = 8.35\ \mathrm{kcal/mol}\tag{12corr}$$

While eq 10 is protobranching compensated, the three isoalkyl type protobranching interactions in the *tert*-butyl radical in eq 12 are not balanced since there are six neo-alkyl type protobranches in neopentane. Since protobranching stabilization attenuates as the number of 1,3 alkyl−alkyl interactions between groups bound to the same carbon center increases (i.e., the stabilization energy per protobranch decreases from propane to isobutane and then to neopentane),[44,45] eqs 13-15 serve as protobranching corrections for *n*-alkyl, iso-alkyl, and neo-alkyl groups.

$$\begin{gathered}\mathrm{CH_3CH_2CH_3 + CH_4 \rightarrow 2CH_3CH_3}\quad \Delta E_{\mathrm{rxn}} = 2.69\ \mathrm{kcal/mol}\\ n\text{-alkyl protobranch} = 2.69\ \mathrm{kcal/mol}\end{gathered}\tag{13}$$

$$\begin{gathered}i\text{-}\mathrm{C_4H_{10} + 2CH_4 \rightarrow 3CH_3CH_3}\quad \Delta E_{\mathrm{rxn}} = 7.69\ \mathrm{kcal/mol}\\ \text{iso-alkyl protobranch} = 7.69/3 = 2.56\ \mathrm{kcal/mol}\end{gathered}\tag{14}$$

$$\begin{gathered}\text{neo-}\mathrm{C_5H_{12} + 3CH_4 \rightarrow 4CH_3CH_3}\quad \Delta E_{\mathrm{rxn}} = 13.30\ \mathrm{kcal/mol}\\ \text{neo-alkyl protobranch} = 13.30/6 = 2.22\ \mathrm{kcal/mol}\end{gathered}\tag{15}$$

Applying the 6(2.22) − 3(2.56) = 5.64 kcal/mol protobranching correction to eq 12 raises the $SE_{CH_3}$ *tert*-butyl radical RSE to 8.35 kcal/mol (eq 12corr), in close agreement with the $SE_H$ value of 8.32 (eq 10). The $SE_{R-R}$ RSE value derived from eq 11 is compromised not only by protobranching imbalances but also by the steric strain in hexamethylethane lost upon cleavage of the central C−C bond to form two *tert*-butyl radicals. ZRM recognized that strain corrections must be made for the $SE_{R-R}$ method to derive the RSE of the *tert*-butyl radical by means of eq 11 satisfactorily. ZRM's 5.8 ± 0.6 kcal/mol strain estimate for hexamethylethane was based on BDE comparisons of neopentane, ethane, *tert*-butanol, and hydrogen peroxide, by using two instances of Pauling's equation (eq 4).[16] Our far simpler, direct, and numerically similar hexamethylethane strain estimate of 6.14 kcal/mol is based on the comparison of its experimental $\Delta_f H^\circ_{298}$, −54.06 kcal/mol, with that given by Benson group increments, −60.20 kcal/mol.[54]

However, ZRM's treatment did not address the protobranching imbalances inherent in the $SE_{R-R}$ (and $SE_Z$) methods. There are 12 neo-alkyl protobranching interactions in hexamethylethane, but only a total of six (three each) in the two *tert*-butyl radical dissociation products. Hence, the protobranching correction, 5.64 kcal/mol, is the same as that derived for the correction of eq 12. Therefore, after accounting for protobranching and strain contaminations, the RSE of the *tert*-butyl radical given by the properly corrected $SE_{R-R}$ method (eq 11corr) is 5.77 (eq 11) + 5.64 (PB) − 6.14/2 (strain) = 8.34 kcal/mol, nearly identical to the RSE values predicted by the $SE_H$ (eq 10) and the corrected $SE_{CH_3}$ (eq 12corr) methods, 8.32 and 8.35 kcal/mol, respectively.

We also contrast the simplicity of our method with the complicated ZRM treatment. This introduces additional reference species and is marred by the questionable reliability of their electronegativity estimates, which are employed to derive "special effects free" BDEs but do not agree with other electronegativity indices in the literature.[40,41]

Similar considerations apply to the other $SE_H$ vs $SE_{CH_3}$ and $SE_{R-R}$ evaluations of Table 1, e.g., the discrepancy in the RSE estimates for the phenyl radical.

$$C_6H_5\bullet + CH_4 \rightarrow C_6H_6 + CH_3\bullet$$
$$SE_H(C_6H_5\bullet) = -7.79\ \text{kcal/mol} \qquad (16)$$

$$C_6H_5\bullet + \frac{1}{2}CH_3CH_3 \rightarrow \frac{1}{2}C_6H_5\text{-}C_6H_5 + CH_3\bullet$$
$$SE_{R\text{-}R}(C_6H_5\bullet) = -13.65\ \text{kcal/mol} \qquad (17)$$

$$C_6H_5\bullet + CH_3CH_3 \rightarrow C_6H_5{-}CH_3 + CH_3\bullet$$
$$SE_{CH_3}(C_6H_5\bullet) = -13.41\ \text{kcal/mol}^* \qquad (18)$$

*$\Delta_f H^\circ$ of the phenyl radical was taken from ref 26.

The $SE_H(C_6H_5\bullet)$ evaluation (eq 16) is straightforward, simple, and easily interpreted. Despite minor hybridization imbalance in the C−H bond energies ($C_6H_6$ larger and $CH_3$ smaller than $CH_4$),[2] the phenyl radical is destabilized primarily by its distorted radical center.

In contrast, the $SE_{R-R}(C_6H_5\bullet)$ evaluation (eq 17) is complicated primarily by the unbalanced conjugation stabilization energy of biphenyl. Since such "special effects" precluded use of the $SE_{R-R}$ method directly, ZRM attempted to derive a "conjugation−free" BDE estimate for biphenyl, based on chlorobenzene, $Cl_2$, toluene, and ethane. Other special effects, e.g., the hyperconjugative stabilization of toluene and the possible stabilization of chlorobenzene, were neglected; the reliability of the ZRM assessment is clouded further by concerns regarding the accuracy of their electronegativity estimates (whose derivations also are subject to contamination by "special effects").

**Table 2. Selected Radical Stabilization Energies (RSE) Relative to $CH_3\bullet$ for the $SE_H$, $SE_{CH_3}$, and $SE_{R-R}$ Schemes after Correcting for Protobranching,[b] Hyperconjugation,[c] Conjugation,[d] and Strain[e] Lost upon the Dissociation of the Parent Hydrocarbon, Compared to the $SE_Z$ RSEs Predicted by ZRM (ref 1)[a]**

| radical | $SE_H$ RSE | $SE_{CH_3}$ RSE | $SE_{R-R}$ RSE | $SE_Z$ RSE |
|---|---|---|---|---|
| $CH_3$ | 0.00 | 0.00 | 0.00 | 0.00 |
| 1° ($C_2H_5\bullet$) | 3.91 | 3.91[b] | 3.86[b] | 1.1 |
| 2° ($i$-$C_3H_7\bullet$) | 6.37 | 6.36[b] | 6.19[b,e] | 1.4 |
| 3° ($t$-$C_4H_9\bullet$) | 8.32 | 8.35[b] | 8.34[b,e] | 3.7 |
| benzyl | 20.72[c] | 20.83[b,c] | 19.88[b,c] | 11.7 |
| allyl | 22.32[c] | 22.43[b,c] | 22.71[b,c] | 14.3 |
| vinyl | −6.05 | -6.02[c] | −6.05[d] | −11.6 |
| phenyl | −7.79 | −7.82[c] | −7.11[d,f] | −13.1 |

[a] $SE_H$, $SE_{CH_3}$, and $SE_{R-R}$ values are based on experimental heats of formation (kcal/mol, 298K) taken from ref 42. Detailed application of the corrections applied to each radical is available in the Supporting Information. [b] 2.69, 2.56, and 2.22 kcal/mol corrections per protobranch lost for *n*-, iso-, and neo-alkanes were derived from eqs 13, 14, and 15 respectively (see text). [c] 5.59 kcal/mol correction for hyperconjugation lost was derived from eqs 21 and 22 (see text). [d] A 14.52 kcal/mol conjugation lost was derived from eq 20. [e] Corrections for strain lost are taken as the difference between experimental heat of formation of the parent hydrocarbon, and its predicted heat of formation based on Benson group increments (see text and ref 54). [f] 1.43 kcal/mol was added to the heat of formation of biphenyl to correct for strain encountered when enforcing the planar ($D_{2h}$) geometry.

$$\text{biphenyl} + 2CH_4 \rightarrow 2C_6H_6 + C_2H_6 + 11.72\ \text{kcal/mol}$$
$$(\text{estimated conjugation energy of biphenyl}) \qquad (19)$$

Isodesmic eq 19 is not without conceptual flaws, but it provides a simpler, direct estimate of the conjugative stabilization of biphenyl. On the basis of the resulting 1/2 × 11.72 = 5.86 correction to eq 17, the derived $SE_{R-R}$ RSE value for the phenyl radical is −13.65 + 5.86 = −7.79 kcal/mol. While this phenyl radical RSE evaluation via $SE_{R-R}$ matches the $SE_H$ estimate (eq 16), this identity is due to the redundancy of the equations employed (1/2 [eq 19 + eq 18] = eq 16). However, alternative estimates of conjugation energies applicable to biphenyl (and related species, see Table 2) are like those of eq 19. Equation 20, which gives a 14.5 kcal/mol conjugation energy estimate for *anti*-butadiene ($C_{2h}$) similar to that predicted via Block Localized Wave function(BLW) analysis,[44] is an example.

$$1,3\text{-}anti\text{-butadiene} + 2CH_4 \rightarrow 2C_2H_4 + C_2H_6$$
$$\text{conjugation energy } 14.52\ \text{kcal/mol} \qquad (20)$$

The experimental $D_2 \rightarrow D_{2h}$ planarization energy of biphenyl is 1.43 kcal/mol.[55] Taking this "strain effect" into account, the corrected biphenyl conjugation energy given by eq 19 is

13.2 kcal/mol. Correcting the $SE_{R-R}$ estimate for the $D_{2h}$ planarization energy, and the resulting enhanced conjugation energy of biphenyl gives $-13.65 + 1/2\ 14.52 - 1/2\ 1.43 = -7.11$, which agrees reasonably well with the $-7.79$ obtained from the more direct $SE_H$ approach.

The $SE_{CH_3}$ evaluation of the RSE of the phenyl radical (eq 18) is complicated by the unbalanced phenyl−methyl hyperconjugation interaction in toluene. Equation 21 gives a 5.62 kcal/mol hyperconjugative stabilization, similar to that of propene (5.56 kcal/mol, eq 22) for which Mo's BLW analyses gave values between 5.0 and 5.9 kcal/mol.[44,56]

$$\text{toluene} + CH_4 \rightarrow C_6H_6 + C_2H_6$$
$$\text{hyperconjugation energy} = 5.62\ \text{kcal/mol} \qquad (21)$$

$$\text{propene} + CH_4 \rightarrow C_2H_4 + C_2H_6$$
$$\text{hyperconjugation energy} = 5.56\ \text{kcal/mol} \qquad (22)$$

We adopt the average $\Delta E_{rxn}$ of eqs 21 and 22, 5.59 kcal/mol, as a general hyperconjugation correction. Thus, our correction to eq 18 is $-13.41 + 5.59 = -7.82$, in close agreement with the direct $SE_H$ and corrected $SE_{R-R}$ data.

Employing similar corrections to the remaining radical set in Table 1 unites their RSEs as well. The values of the corrected RSEs and the applied corrections are presented in Table 2. Note the close agreement between all three RSE estimates results from the removal of extraneous interactions in the $SE_{CH_3}$ and $SE_{R-R}$ equations and that the $SE_H$ method is the simplest and most direct means of obtaining relative RSEs with near inherent character.

Poutsma highlighted the superior applicability of the $SE_H$ method further by pointing out that only $SE_H$ RSEs predict the isomerization energies of alkyl radical isomers with identical carbon skeletons directly. In contrast, the $SE_{CH_3}$, $SE_{R-R}$, and $SE_Z$ approaches all underestimate these differences. For example, secondary radicals are 2.4 to 2.7 kcal/mol more stable than their primary radical isomers experimentally (e.g., 2.6 kcal/mol for 2−vs 1−propyl), but the $SE_{CH_3}$, $SE_{R-R}$ and $SE_Z$ methods give only 0.2, 1.0, and 0.3 kcal/mol, respectively (Table 1). In sharp contrast, the 2°−1° $SE_H$ difference, 2.46 kcal/mol (based on ethyl vs i-propyl, see Tables 1 and 2), agrees with the isomerization energy. The 2°−1° difference in BDEs for all experimentally available data are 2.4 kcal/mol.[12] The $SE_Z$ shortcomings are similar for primary-tertiary RSE differences (see Tables 1 and 2). The experimental *tert*-butyl−isobutyl radical energy difference, 5.1 kcal/mol,[41] compares with the 4.4 ± 0.6 kcal/mol ethyl vs *tert*-butyl $SE_H$ difference but not with the 1.5, 3.3, and 2.6 kcal/mol 3°−1° differences given directly by the $SE_{CH_3}$, $SE_{R-R}$ and $SE_Z$ methods (Table 1).

ZRM attribute the agreement of radical isomerization energies with those given by $SE_H$ differences to the redundancy of the derivations involved. However, we emphasize that the radical isomerization energies derived from experimental data are not necessarily the same as the actual $SE_H$ energy differences, particularly when the latter are based on the average of available 1°, 2° and 3° alkyl radical data. Unlike the $SE_{CH_3}$, $SE_{R-R}$ and $SE_Z$ methods, the $SE_H$ method achieves the skeletal balance inherent in comparisons of isomers.

However, even the $SE_H$ method is not without complications. The dissociation of a hydrogen atom from the methyl groups both of toluene and propene results in the loss of their stabilizing $\pi$ hyperconjugation interactions. Thus, the RSEs of the benzyl and allyl radicals given by eq 1 (see Table 1) are too low compared to their hyperconjugation-corrected conjugation energies (Table 2).

ZRM recently issued another criticism of the $SE_H$ method. Using the RSEs determined from eqs 1 and 3b and eq 23 to compute the BDEs of a set of 13 hydrocarbons, ZRM reported excellent agreement with experiment for the $SE_Z$ method (eq 3b), whereas the $SE_H$ method (eq 1) performed less satisfactorily (see Table 3).

$$\mathrm{BDE}[\mathrm{R\text{-}R'}] = \mathrm{BDE}[CH_3{-}CH_3] - \mathrm{SE}[\mathrm{R}\bullet] - \mathrm{SE}[\mathrm{R'}\bullet] \qquad (23)$$

In all these cases, the BDEs given by the $SE_Z$ method agree within experimental error (Table 3) whereas the values given directly by $SE_H$ are too low.[25] Noting this numeric disagreement, ZRM stated, "$SE_H$ values, *by themselves*, do not provide a quantitative measure of radical stabilization energies." Yet this inference is highly misleading, since the disagreement between the $SE_H$-derived and experimental BDEs is not due to the energies of the dissociated radicals *by themselves*, but rather to imbalances involving the change in the number of protobranching[44] and hyperconjugation[57−63] interactions in the R−R′ reference molecules and in their separated radical fragments. *Thus, there is no reason to expect RSEs derived from direct use of the $SE_H$ method to reproduce experimental R−R′ BDEs.*

$SE_H$ RSEs can be used to calculate the BDEs of the Table 3 species provided explicit corrections are made for the loss of protobranching and hyperconjugation interactions ("PB loss" and "HC loss") upon cleavage of the parent compound as shown in eq 24.

$$\mathrm{BDE}[\mathrm{R\text{-}R'}] = \mathrm{BDE}[CH_3{-}CH_3] + \text{PB loss}$$
$$+ \text{HC loss} - \mathrm{RSE}[\mathrm{R}\bullet] - \mathrm{RSE}[\mathrm{R'}\bullet] \qquad (24)$$

The PB loss and HC loss terms are derived from the energies of the isodesmic equations that define protobranching (eqs 13, 14, and 15) and hyperconjugation (the average of eqs 21 and 22). The BDEs of the selected hydrocarbons computed by the $SE_H$ and $SE_Z$ methods using eq 24 are presented in Table 4, and the applied protobranching and hyperconjugation corrections are listed in Table 5. Note the corrected $SE_H$-derived BDEs in Table 4 are nearly identical to experiment, while those based on $SE_Z$ are overestimated. Moreover, eq 24 is interpretively superior to eq 23, since the impact of losses in protobranching and hyperconjugation interactions caused by bond cleavage in the parent compound are treated explicitly.

Although the $SE_Z$ RSEs reproduce experimental BDE[R−R′] values accurately via eq 23, the loss of individual interactions (both stabilizing and destabilizing) present in the parent R−R′ compound upon bond cleavage are hidden in the evaluation. The method ignores properties such as C−C bond energies, hyperconjugation, and conjugation stabilization of the radical, as well as loss of protobranching, hyperconjugation, and conjugation interactions in the parent hydrocarbon. Although ZRM attempt to remove the influence of steric strain from the parent compounds (necessary for their technique to function satisfactorily), the energies of other effects are not elucidated when analyzing BDEs. Hence, the $SE_Z$ model fails as an interpretive tool.

**Theoretical Inherent Alkyl Radical RSE Computations.** The relative magnitudes (e.g., tertiary > secondary > primary) of the RSEs of simple alkyl radicals, traditionally defined by eq 1, have been attributed to greater hyperconjugative stabilization of the more highly alkylated radicals. To test this premise, we employed

Table 3. Bond Dissociation Energies (kcal mol$^{-1}$) Calculated by eq 23 using SE$_H$ and SE$_Z$ Carbon Radical Stabilization Energies in Table 1

| R−R′ | BDE [R−R′] by SE$_H$ eq 23[a] | BDE [R−R′] expt[b] | BDE [R−R′] by SE$_Z$ eq 23[a] |
|---|---|---|---|
| $CH_3-CH_2CH_3$ | 86.29 | 88.2 ± 0.5 | 89.1 |
| $CH_2{=}CHCH_2-CH_2Ph$ | 58.34 | 62.9 ± 1.2 | 64.2 |
| $CH_3CH_2-CH_2CH_3$ | 82.38 | 87.4 ± 0.7 | 88.0 |
| $CH_3CH_2-CH(CH_3)_2$ | 79.92 | 87.1 ± 0.7 | 87.7 |
| $CH_3-Ph$ | 97.99 | 103.8 ± 2.0 | 103.3 |
| $(CH_3)_2CH-CH{=}CH_2$ | 89.88 | 99.9 ± 1.1 | 100.4 |
| $PhCH_2-CH_2CH_3$ | 71.16 | 76.0 ± 1.1 | 77.4 |
| $CH_3CH_2-CH_2CH{=}CH_2$ | 69.56 | 74.7 ± 0.9 | 74.8 |
| $(CH_3)_2CH-CH_2Ph$ | 68.70 | 76.7 ± 1.1 | 77.1 |
| $CH_3CH_2-CH{=}CH_2$ | 92.34 | 100.2 ± 1.1 | 100.7 |
| $CH_3CH_2-Ph$ | 94.08 | 101.5 ± 2.1 | 102.2 |
| $(CH_3)_2CHCH_2-CH{=}CH_2$ | 92.34 | 99.8 ± 1.1 | 100.7 |
| $CH_2{=}CHCH_2-CH_2CH{=}CH_2$ | 56.74 | 61.4 ± 0.8 | 61.6 |

[a] $CH_3-CH_3$ BDE of 90.20 kcal/mol was employed. [b] Experimental BDEs are taken from ref 1.

Table 4. Bond Dissociation Energies (kcal mol$^{-1}$) Calculated by eq 24 using SE$_H$ and SE$_Z$ Carbon Radical Stabilization Energies in Table 2

| R−R′ | BDE [R−R′] by SE$_H$ eq 24[a] | BDE [R−R′] expt eq 24[b] | BDE [R−R′] by SE$_Z$ eq 24[a] |
|---|---|---|---|
| $CH_3-CH_2CH_3$ | 88.98 | 88.2 ± 0.5 | 91.79 |
| $CH_3CH_2-CH_2CH_3$ | 87.76 | 87.4 ± 0.7 | 93.38 |
| $CH_3CH_2-CH(CH_3)_2$ | 87.6 | 87.1 ± 0.7 | 95.38 |
| $CH_3-Ph$ | 103.58 | 103.8 ± 2.0 | 108.89 |
| $(CH_3)_2CH-CH{=}CH_2$ | 100.46 | 99.9 ± 1.1 | 110.98 |
| $PhCH_2-CH_2CH_3$ | 76.57 | 76.0 ± 1.1 | 88.37 |
| $CH_3CH_2-CH_2CH{=}CH_2$ | 74.97 | 74.7 ± 0.9 | 85.77 |
| $CH_2{=}CHCH_2-CH_2Ph$ | 63.78 | 62.9 ± 1.2 | 80.76 |
| $(CH_3)_2CH-CH_2Ph$ | 76.41 | 76.7 ± 1.1 | 90.37 |
| $CH_3CH_2\text{-}{-}CH{=}CH_2$ | 100.62 | 100.2 ± 1.1 | 108.98 |
| $CH_3CH_2-Ph$ | 102.36 | 101.5 ± 2.1 | 110.48 |
| $(CH_3)_2CHCH_2-CH{=}CH_2$ | 100.62 | 99.8 ± 1.1 | 108.98 |
| $CH_2{=}CHCH_2-CH_2CH{=}CH_2$ | 62.18 | 61.4 ± 0.8 | 78.16 |

[a] $CH_3-CH_3$ BDE of 90.20 kcal/mol was employed. [b] Experimental BDEs are taken from ref 1.

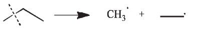
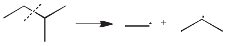
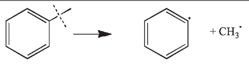
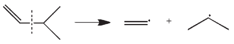
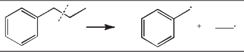
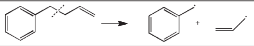
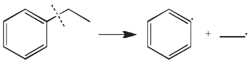
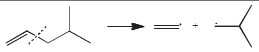
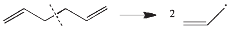
Block Localized Wave function (BLW) and Natural Bond Orbital (NBO) analyses to probe the magnitude of radical hyperconjugative stabilization directly.

The BLW implementation of valence bond theory defines a localized wave function corresponding to a Lewis structure where the electrons are confined to bonds or to atoms (e.g., as radicals).[56,64] The vertical delocalization energy (VDE)[27,29] corresponds to the increase in energy due to this localization, compared to the energy of the fully delocalized wave function at the same geometry. This VDE for a radical is a measure of its intrinsic stabilization from all its interactions, e.g., geminal as well as vicinal. Relaxation of the geometry, but still within the localized BLW constraint, gives the adiabatic delocalization energy (ADE). In effect, the radical itself serves as its own reference in both of these "absolute" evaluations, but it must be kept in mind that the radical precursors, even the parent alkanes, also have appreciable BLW delocalization energies (VDE and ADE). Hence, the greater DEs of the radical compared to those of its parent hydrocarbon, as well as the origins of these energies and their interpretations, also are important. We will discuss full details in a separate paper; the evaluation of hyperconjugation suffices here.

The alkyl radical hyperconjugation energy (RHE) can be approximated by the difference between the VDEs of the radical and its parent alkane, relative to the ΔVDE for $CH_4 \rightarrow CH_3\bullet$ (where hyperconjugation is not possible). Such RHEs are lower limits, as the BLW procedure "turns off" a greater number of stabilizing HCCH hyperconjugation interactions in the reference alkanes[27,65,66] than in the corresponding radicals. As a simple illustration, there are three stabilizing HCCH hyperconjugation interactions in both staggered and eclipsed ethane;[27,65,66] only two of these HCCH's remain in $C_2H_5\bullet$ since one is replaced by the HCC• hyperconjugation. Nevertheless, the decrease in alkane C−H BDEs with increasing alkyl substitution (Table 6, SE$_H$ data) is matched reasonably well by the greater hyperconjugative stabilization of the corresponding 1°−2°−3° RHE BLW radical data.

The NBO formalism expresses a molecular wave function in terms of natural bond orbitals (NBOs). This orthonormal maximum occupancy set of localized one and two center orbitals

Table 5. Total and Individual $SE_{lost}$ Corrections for ZRM's Set of 13 Bond Dissociation Reactions[a]

| Bond dissociation reaction | Sum of "lost" interactions (kcal/mol) | Protobranching imbalances<br>n-pb=2.69<br>i-pb=2.56 | Hyperconjugation (hc) imbalances<br>hc=5.59 |
|---|---|---|---|
|  | 2.69 | 1 n-pb | - |
|  | 5.38 | 2 n-pb | - |
|  | 7.68 | 3 i-pb | - |
|  | 5.59 | - | 1 |
|  | 10.58 | 3i-pb→1n-pb | 1 |
|  | 10.97 | 2 n-pb | 1 |
|  | 10.97 | 2 n-pb | 1 |
|  | 16.53 | 2 n-pb | 2 |
|  | 13.27 | 3 i-pb | 1 |
|  | 8.28 | 1 n-pb | 1 |
|  | 8.28 | 1 n-pb | 1 |
|  | 8.28 | 1 n-pb | 1 |
|  | 16.56 | 2 n-pb | 2 |

[a] Only the immediate environment of the specific bond being cleaved is considered. *n*-Alkyl and iso-alkyl protobranching imbalances are labeled n-pb and i-pb.

Table 6. Comparison of BLW and NBO Derived Relative Radical Hyperconjugation Energies (RHE) with the Relative C−H BDEs Predicted by the $SE_H$, $SE_{CH_3}$, and $SE_Z$ Methods[a]

| alkane C−H | BLW-RHE | NBO-RHE | via $SE_H$ | via $SE_{CH_3}$ | via $SE_Z$ |
|---|---|---|---|---|---|
| $CH_4 \rightarrow CH_3\bullet$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 |
| $C_2H_6 \rightarrow C_2H_5\bullet$ | 2.50 | 3.03 | 3.91 | 1.22 | 1.1 |
| $C_3H_8 \rightarrow i\text{-}C_3H_7\bullet$ | 5.70 | 6.20 | 6.37 | 1.37 | 1.4 |
| $i\text{-}C_4H_{10} \rightarrow t\text{-}C_4H_9\bullet$ | 8.62 | 9.68 | 8.32 | 2.71 | 3.7 |

[a] Energies in kcal/mol are relative to $CH_4 \rightarrow CH_3\cdot$. The BLW RHEs were computed with the XMVB program.[68] Due to constraints regarding the maximum number of primitive basis functions allowed in the XMVB suite, the HF/6-31+G* level of theory was employed. The NBO RHEs were computed at HF/6-311+G**.

typically accounts for >99% of the total molecular electron density.[67] Sets of low occupancy Rydberg and antibonding orbitals augment the NBOs and complete the description of the wave function. The hyperconjugative stabilization of an alkyl radical center was evaluated simply by computing the increase in energy when the radical $\pi^*$ acceptor orbital is deleted. Since the BDE equations used to define RSEs also involve the loss of a $C-H\sigma \rightarrow C-H\sigma^*$ interaction in the parent alkane, the RSE of an alkyl radical is computed as the hyperconjugation energy difference between the radical and parent alkane. Similar to the BLW findings, the decrease in alkane C−H BDEs with increasing alkyl substitution (Table 6, data via $SE_H$) is matched by the hyperconjugative stabilization of the corresponding 1°−2°−3° RHE NBO data.

The results in Table 6 not only support the hyperconjugation explanation for the decreased C−H BDEs of more highly substituted alkanes impressively but also highlight the advantage of using the C−H BDE of methane as the basis for defining RSEs. All other evaluations using experimental data suffer from uncompensated imbalances, which are absent or minimal in $SE_H$ evaluations.

This criticism applies even to ethane. Extensive investigations of the origin of its rotation barrier all agree that the HCCH hyperconjugation energy is substantial in both the staggered and eclipsed conformations.[27,65,66,69−71] Vicinal Pauli repulsion occurs as well.[72,73] The loss of these interactions on CC bond dissociation further complicates the interpretation of $SE_{CH_3}$ and $SE_{R-R}$ data. Such problems with vicinal R−R and R−R′ interactions are either absent or minimized in the R−H systems upon which $SE_H$ data are based.

## CONCLUSIONS

RSEs evaluated by the $SE_H$, $SE_{CH_3}$, and $SE_{R-R}$ methods give the same qualitative order of radical stability. We have shown their quantitative disagreements arise from extraneous interactions lost upon cleavage of the $R-CH_3$ and R−R bonds in the $SE_{CH_3}$ and $SE_{R-R}$ methods. Buried in each of the RSEs derived from the $SE_{CH_3}$ and $SE_{R-R}$ methods are a complex array of effects involving the initial hydrocarbons (including the inherent C−C bond energies, the relief of steric strain and Pauli repulsion between their R and R′ groups, and the loss of their protobranching, conjugative, and hyperconjugative stabilization) and in the dissociated R• and R′• radicals (including hyperconjugative and conjugative stabilization). ZRM's refinement of the $SE_{R-R}$ method ($SE_Z$) attempts to compensate for the loss of conjugation and steric strain in radical precursors when present, but the other factors mentioned are not taken into account in their analysis.

Both $SE_H$ and $SE_Z$ values can be utilized to calculate C−C BDEs of ZRM's 13 hydrocarbon test set accurately. Although values derived *directly* from the $SE_H$ procedure do not match experiment, *this cannot be expected* since changes in the number of protobranching and/or hyperconjugation interactions lost upon bond cleavage of the parent compound are not considered. We have proposed a simple refinement of the $SE_H$ treatment (eq 24), which includes explicit corrections for losses in the number of protobranching and hyperconjugation interactions, and reproduces experimental C−C BDEs.

The $SE_H$ method relies on straightforward stabilization energy assessments. Its RSE values, based on the dissociation of hydrogen from R, are the less compromised by extraneous interactions in the radical precursors than any other method for obtaining RSEs from BDEs. The $SE_H$ method gives RSEs, which agree reasonably well with BLW and NBO theoretical estimates of alkyl radical stabilization due to hyperconjugation and is the simplest and most direct means for obtaining RSEs from BDE data. Moreover, the concept of protobranching[44] by itself unifies most of the RSE estimates for the simple alkyl radicals discussed here derived from R−H, $R-CH_3$, or R−R′ BDEs.

## ASSOCIATED CONTENT

**Supporting Information.** This material is available free of charge via the Internet at http://pubs.acs.org.

## AUTHOR INFORMATION

**Corresponding Author**
*E-mail: schleyer@uga.edu.

## ACKNOWLEDGMENT

NSF Grant CHE-0716718 and TeraGrid resources provided by NCSA Abe and Cobalt (TG-CHE100088) supported this research. We also thank Yirong Mo warmly for advice and methodological developments, Judy I. Wu, Clémence Corminboeuf, and Carl Kemnitz, one of the referees of this paper, for helpful discussions.

## REFERENCES

(1) Zavitsas, A. A.; Rogers, D. W.; Matsunaga, N. *J. Org. Chem.* **2010**, *75*, 5697.

(2) Exner, K.; Schleyer, P. v. R. *J. Phys. Chem. A* **2001**, *105*, 3407.

(3) Berkowitz, J.; Ellison, G. B.; Gutman, D. *J. Phys. Chem.* **1994**, *98*, 2744.

(4) Yao, X.-Q.; Hou, X.-J.; Jiao, H.; Xiang, H.-W.; Li, Y.-W. *J. Phys. Chem. A* **2003**, *107*, 9991.

(5) Johnson, E. R.; Clarkin, O. J.; DiLabio, G. A. *J. Phys. Chem. A* **2003**, *107*, 9953.

(6) Feng, Y.; Liu, L.; Wang, J.-T.; Huang, H.; Guo, Q.-X. *J. Chem. Inf. Comput. Sci.* **2003**, *43*, 2005.

(7) Izgorodina, E. I.; Coote, M. L.; Radom, L. *J. Phys. Chem. A* **2005**, *109*, 7558.

(8) Agapito, F.; Nunes, P. M.; Cabral, B. J. C.; dos Santos, R. M. B.; Simoes, J. A. M. *J. Org. Chem.* **2007**, *72*, 8770.

(9) Nunes, P. M.; Estacio, S. G.; Lopes, G. T.; Cabral, B. J. C.; dos Santos, R. M. B.; Simoes, J. A. M. *Org. Lett.* **2008**, *10*, 1613.

(10) Hemelsoet, K.; van Speybroeck, V.; Waroquier, M. *J. Phys. Chem. A* **2008**, *112*, 13566.

(11) van Zeist, W.-J.; Bickelhaupt, F. M. *Phys. Chem. Chem. Phys.* **2009**, *11*, 10317.

(12) (a) Zhang, I. Y.; Wu, J.; Luo, Y.; Xu, X. *J. Chem. Theory Comput.* **2010**, *6*, 1462. (b) Luo, Y.-R. *Handbook of Bond Dissociation Energies*; CRC Press: New York, 2003.

(13) Cox, R. D.; Pilcher, G. *Thermochemistry of Organic and Organometallic Compounds*; Academic Press: New York, 1970.

(14) Pedley, J. B.; Naylor, R. D.; Kirby, S. P. *Thermochemical Data of Organic Compounds*; Chapman and Hall: London, 1986.

(15) Cohen, N. *J. Phys. Chem. Ref. Data* **1996**, *25*, 1411.

(16) Matsunaga, N.; Rogers, D. W.; Zavitsas, A. A. *J. Org. Chem.* **2003**, *68*, 3158.

(17) Zavitsas, A. A. *J. Org. Chem.* **2008**, *73*, 9022.

(18) Hehre, W. J.; Radom, L.; Schleyer, P. v. R.; Pople, J. A. *Ab Initio Molecular Orbital Theory*; John Wiley & Sons: New York, 1986.

(19) Parkinson, C. J.; Mayer, P. M.; Radom, L. *Theor. Chem. Acc.* **1999**, *102*, 92.

(20) Parkinson, C. J.; Mayer, P. M.; Radom, L. *J. Chem. Soc., Perkin Trans. 2* **1999**, *11*, 2305.

(21) Henry, D. J.; Parkinson, C. J.; Mayer, P. M.; Radom, L. *J. Phys. Chem. A* **2001**, *105*, 6750.

(22) Campos, L. M.; Dang, H.; Ng, D.; Yang, Z.; Martinez, H. L.; Garcia-Garibay, M. A. *J. Org. Chem.* **2002**, *67*, 3749.

(23) Menon, A. S.; Radom, L. *J. Phys. Chem. A* **2008**, *112*, 13225.

(24) Goerigk, L.; Grimme, S. *J. Chem. Theory Comput.* **2010**, *6*, 107.

(25) Poutsma, M. L. *J. Org. Chem.* **2008**, *73*, 8921.

(26) Blanksby, S. J.; Ellison, G. B. *Acc. Chem. Res.* **2003**, *36*, 255.

(27) Mo, Y. *J. Org. Chem.* **2010**, *75*, 2733.

(28) Wertz, J. E.; Bolton, J. R. *Electron Spin Resonance, Elementary Theory and Practical Applications*, 2nd ed.; J. Wiley & Sons: New York, 2007.

(29) Mo, Y.; Hiberty, P. C.; Schleyer, P. v. R. *Theor. Chem. Acc.* **2010**, *127*, 27.

(30) Coote, M. L.; Pross, A.; Radom, L. *Org. Lett.* **2003**, *5*, 4689.

(31) Rüchardt, C. *Angew. Chem., Int. Ed.* **1970**, *9*, 830.

(32) Coote, M. L.; Lin, C. Y.; Beckwith, A. L. J.; Zavitsas, A. A. *Phys. Chem. Chem. Phys.* **2010**, *12*, 9597.

(33) Poutsma, M. L. *J. Org. Chem.* **2011**, *76*, 270.

(34) Pauling, L. *J. Am. Chem. Soc.* **1932**, *54*, 3570.

(35) Pauling, L. C. *The Nature of the Chemical Bond*, 3rd ed.; Cornell University Press: Ithaca, 1960.

(36) Pauling values are given as 2.5 or 2.55 for C and 2.1 or 2.2 for H in various textbooks. See ref 34.

(37) Other electonegativity scales: H, 2.25; C, 2.48 ($sp^3$) Mulliken-Jaffé; H, 2.300; C, 2.544. Allen gave even smaller C,H difference. See ref 58.

(38) Signorell, R.; Marquardt, R.; Quack, M.; Suhm, M. A. *Mol. Phys.* **1996**, *89*, 297.

(39) Hollenstein, H.; Marquardt, R.; Quack, M.; Suhm, M. A. *J. Chem. Phys.* **1994**, *101*, 3588.

(40) Huheey, J. E. *J. Phys. Chem.* **1965**, *69*, 3284.

(41) Cao, C.; Luo, J. *QSAR Comb. Sci.* **2007**, *26*, 955.

(42) NIST Computational Chemistry Comparison and Benchmark Database, NIST Standard Reference Database Number 101 Release 15a, April 2010; R. D. Johnson III, Ed.; http://cccbdb.nist.gov/. Afeefy, H. Y.; Liebman, J. F.; Stein, S. E. Neutral Thermochemical Data. In *NIST Chemistry WebBook*, NIST Standard Reference Database Number 69; Linstrom, P. J., Mallard, W. G., Eds.; National Institute of Standards and Technology: Gaithersburg, MD, 2004; http://webbook.nist.gov/.

(43) ZRM derived a value of 1.1 kcal/mol for this equation using different experimental data. We employ NIST values.

(44) Wodrich, M. D.; Wannere, C. S.; Mo, Y.; Jarowski, P. D.; Houk, K. N.; Schleyer, P. v. R. *Chem.—Eur. J.* **2007**, *13*, 7731.

(45) Wodrich, M. D.; Schleyer, P. v. R. *Org. Lett.* **2006**, *8*, 2135.

(46) Wodrich, M. D.; Corminboeuf, C.; Schleyer, P. v. R. *Org. Lett.* **2006**, *8*, 3631.

(47) Wodrich, M. D.; Jana, D. F.; Schleyer, P. v. R.; Corminboeuf, C. *J. Phys. Chem. A* **2008**, *112*, 11495.

(48) Estrada, E. *Chem. Phys. Lett.* **2008**, *463*, 422.

(49) Kemnitz, C. R.; Mackey, J. L.; Loewen, M. J.; Hargrove, J. L.; Lewis, J. L.; Hawkins, W. E.; Nielsen, A. F. *Chem.—Eur. J.* **2010**, *16*, 6942.

(50) Schleyer, P. v. R.; McKee, W. C. *J. Phys. Chem. A* **2010**, *114*, 3737.

(51) Gonthier, J. F.; Wodrich, M. D.; Steinmann, S. N.; Corminboeuf, C. *Org. Lett.* **2010**, *12*, 3070.

(52) Ess, D. H.; Liu, S.; De Proft, F. *J. Phys. Chem. A* **2010**, *114*, 12952.

(53) We will discuss the origins of protobranching in a forthcoming paper. Note the increasing support for this concept, e.g., in refs 25, 29, and 48−52, and Wodrich, M. D.; Corminboeuf, C.; Schreiner, P. R.; Fokin, A. A.; Schleyer, P. v. R. *Org. Lett.* **2007**, *9*, 1851. For critical views, see: Gronert, S. *Chem.—Eur. J.* **2009**, *15*, 5372. Fishtik, I. *J. Phys. Chem. A* **2010**, *114*, 3731.

(54) Cohen, N.; Benson, S. W. *Chem. Rev.* **1993**, *93*, 2419.

(55) Bastianson, O.; Samdal, S. *J. Mol. Struct.* **1985**, *128*, 115.

(56) Mo, Y.; Peyerimhoff, S. D. *J. Chem. Phys.* **1998**, *109*, 1687.

(57) Mulliken, R. S. *J. Chem. Phys.* **1939**, *7*, 339.

(58) Mulliken, R. S.; Rieke, C. A.; Brown, W. G. *J. Am. Chem. Soc.* **1941**, *63*, 41.

(59) Gibson, J. F.; Ingram, D. J. E.; Symons, M. C. R.; Townsend, M. G. *Trans. Faraday Soc.* **1957**, *53*, 914.

(60) Muller, N.; Mulliken, R. S. *J. Am. Chem. Soc.* **1958**, *80*, 3489.

(61) Mulliken, R. S. *Tetrahedron* **1959**, *5*, 253.

(62) Mulliken, R. S. *Tetrahedron* **1959**, *6*, 68.

(63) Symons, M. C. R. *Tetrahedron* **1962**, *18*, 333.

(64) Mo, Y.; Gao, J. L.; Peyerimhoff, S. D. *J. Chem. Phys.* **2000**, *112*, 5530.

(65) Wu, W.; Ma, B.; Wu, J. I.-C.; Schleyer, P. v. R.; Mo, Y. *Chem.—Eur. J.* **2009**, *15*, 9730.

(66) Mo, Y.; Gao, J. *Acc. Chem. Res.* **2007**, *40*, 113.

(67) Weinhold, F.; Landis, C. *Valency and Bonding, A Natural Bond Orbital Donor-Acceptor Perspective*, 1st ed.; Cambridge University Press: Cambridge, 2005.

(68) Song, L.; Mo, Y.; Zhang, Q.; Wu, W. *J. Comput. Chem.* **2005**, *26*, 514.

(69) Goodman, L.; Phophristic, V. *Nature* **2001**, *411*, 565.

(70) Weinhold, F. *Nature* **2001**, *411*, 539.

(71) Weinhold, F. *Angew. Chem., Int. Ed.* **2003**, *42*, 4188.

(72) Badenhoop, J. K.; Weinhold, F. *Int. J. Quantum Chem.* **1999**, *72*, 269.

(73) Bickelhaupt, F. M.; Baerends, E. J. *Angew. Chem., Int. Ed.* **2003**, *42*, 4183.