Macromolecules **2005,** *38,* 1415−1433 **1415**

Effect of Substituents on Radical Stability in Reversible Addition Fragmentation Chain Transfer Polymerization: An ab Initio Study

Michelle L. Coote* and David J. Henry[†]

Research School of Chemistry, Australian National University, Canberra, ACT 0200, Australia

Received October 21, 2004; Revised Manuscript Received November 24, 2004

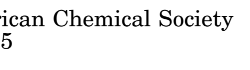
ABSTRACT: The effects of the R- and Z-substituents on radical stability in the reversible addition fragmentation chain transfer (RAFT) polymerization process have been studied via high level ab initio molecular orbital calculations. Radical stabilization energies (RSEs) of the RAFT-adduct radicals $CH_3SC^\bullet ZSR$ and corresponding leaving group radicals $R^\bullet$ have been calculated for various combinations of Z = H, Cl, C≡CH, CH=CH$_2$, CN, CF$_3$, NH$_2$, CH$_3$, Ph, Bz, naphthyl, OCH$_3$, OCH$_2$CH$_3$, OCH(CH$_3$)$_2$, and OC(CH$_3$)$_3$ and R = CH$_2$CN, C(CH$_3$)$_2$CN, Bz, CH(Ph)CH$_3$, C(Ph)(CH$_3$)$_2$, CH$_2$COOCH$_3$, CH(COOCH$_3$)CH$_3$, CH$_2$OCOCH$_3$, and CH$_2$CH$_3$. The results were used in combination with the corresponding values of the enthalpies of the fragmentation reactions, $CH_3SC^\bullet(Z)SR \rightarrow CH_3SC(Z){=}S + {}^\bullet R$ and $CH_3SC^\bullet(Z)SR \rightarrow {}^\bullet CH_3 + S{=}C(Z)SR$, to examine the effects of the substituents on the stability of both the RAFT-adduct radicals and the corresponding thiocarbonyl compounds. The RAFT-adduct radicals are stabilized by electron donation from the two sulfur substituents, and this stability can be further enhanced by unsaturated π-accepting substituents (such as CN, phenyl, and naphthyl). In contrast, lone pair donor Z-substituents (such as Cl, NH$_2$, and OCH$_3$) have a much smaller effect on radical stability. The R-group, which can modify the donation ability of the SR-group, has a minimal effect on the stability of the RAFT-adduct as it is buffered by the second sulfur substituent. However, these orbital interactions do affect the strength of the breaking S−R bond, and this provides an important contribution to the trends in the fragmentation enthalpies. Steric effects on radical stability are also important, with bulky R- and Z-groups inducing conformational changes that interfere with these orbital interactions, sometimes with unexpected consequences. The substituent effects on the RAFT agents are qualitatively different; the agents are strongly stabilized by the lone pair donor Z-substituents and strongly destabilized by electron withdrawing groups (such as CN and CF$_3$) in the R- and Z-positions. Moreover, steric effects are generally more significant, with bulky R- and Z-groups destabilizing the RAFT agent more than the corresponding RAFT-adduct radicals. As part of this work, the accuracy of the low-cost RMP2/6-311+G(3df,2p) method for studying addition−fragmentation processes in RAFT polymerization was evaluated.

1. Introduction

Techniques for controlling free-radical polymerization are an important new development as they allow for the production of polymers with narrow molecular weight distributions, designer end-groups, and novel architectures, such as star polymers and graft polymers.[1−3] Among the most versatile of these new techniques is the reversible addition fragmentation chain transfer (RAFT) process, which was developed by the CSIRO group[1,4] by combining their earlier work on addition−fragmentation reactions of macromonomers[5] with the small radical chemistry of Zard and co-workers.[6] A related process (termed MADIX) in which xanthates are used as the controlling agents was independently developed by the Rhodia group and published shortly after.[7,8] The RAFT process has been successfully applied to a wide range of olefinic monomers, including styrene, the acrylates, acrylic acid, the methacrylates, vinyl acetate, and the acrylamides.[9] The technique has also been used under a variety of conditions, including in the aqueous phase,[10] on the surface of silica,[11] and in emulsion polymerization,[12] and for a number of different applications, including light-emitting nanoporous films,[13] pH-dependent self-assembling polymer micelles,[14] and light-harvesting polymers.[15]

The basic principle of the RAFT process is to protect the majority of the propagating species from bimolecular termination reactions through their reversible trapping into a dormant thiocarbonyl compound via the degenerative transfer reaction shown in Scheme 1.[1] In this way, although the absolute rate of bimolecular termination is similar to that in conventional free-radical polymerization, the relative rate of termination is minimized with respect to the number of growing polymeric chains, and most of the chains bear the thiocarbonyl functionality and remain (potentially) active throughout the polymerization process. However, to achieve this, a delicate balance of the rate coefficients of the competing reactions within the process is required to ensure that the concentration of the dormant species is orders of magnitude greater than that of the active species and that the exchange between the two forms is rapid. An improved understanding of the effects of substituents on these reactions can assist in the design of optimal RAFT agents for controlling new and difficult monomers.

Already a number of theoretical, [16−20] semiempirical,[21−23] and experimental[22−28] studies have examined the effects of substituents on the RAFT process. Perhaps the most striking observation from this previous work is the dramatic effect of substituents on the addition−fragmentation equilibrium:



$$R'S{-}C({=}S)Z + R^\bullet \underset{k_{frag}}{\overset{k_{add}}{\rightleftharpoons}} R'S\dot{C}(Z)SR \qquad (1)$$

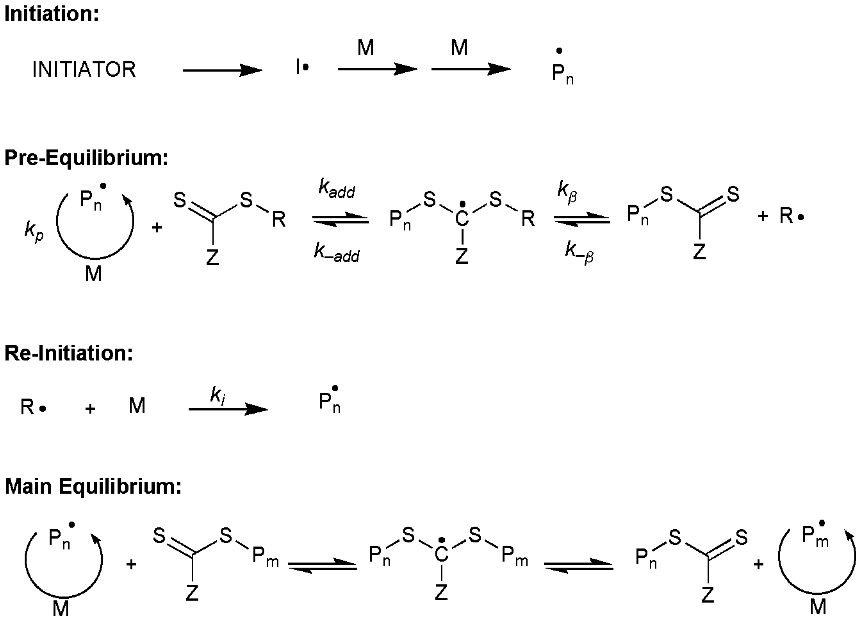
---

* To whom correspondence should be addressed. E-mail: mcoote@rsc.anu.edu.au.

[†] Current address: Applied Physics, School of Applied Sciences, RMIT University, GPO Box 2476V, Melbourne VIC 3001, Australia.

10.1021/ma047814a CCC: $30.25

Scheme 1. Mechanism of RAFT Polymerization



For example, the calculated equilibrium constant ($K_{eq} = k_{add}/k_{frag}$) for a small model of the addition−fragmentation equilibrium in xanthate-mediated polymerization of vinyl acetate (R′ = CH_3, R = CH_2OCOCH_3, and Z = OCH_3) is 7.6×10^{-2} L mol^{-1} at 60 °C.[18,57] In contrast, the corresponding equilibrium constant for a small model of cumyl dithiobenzoate mediated polymerization of methyl acrylate (R′ = CH_3, R = CH_2COOCH_3, and Z = Ph) is 1.5×10^{6} L mol^{-1}—a variation of nearly 8 orders of magnitude.[17] Likewise, experimental studies have reported surprisingly large variations in the apparent chain transfer constant[30] for a series of RAFT agents (differing only in their R- or Z-substituent) in polymerizations with a constant monomer.[22,23,28] For example, in styrene polymerization, apparent chain transfer constants for agents of the form S=C(Z)SCH_2Ph vary from 0.01 (for Z = NEt_2) to 26 (for Z = Ph), while apparent chain transfer constants for the agents S=C(Ph)S−R in methyl methacrylate polymerization vary from 0.03 (R = CH_2Ph) to 13 (R = $C(CH_3)_2CN$).[28] It is this sensitivity of the addition−fragmentation equilibrium that not only accounts for problems in optimizing the RAFT process for certain monomers but also highlights the potential for achieving control in such difficult cases through careful manipulation of the R- and Z-substituents.

In an attempt to explain these dramatic substituent effects, a number of common themes are emerging from both the theoretical and the experimental studies. In particular, it has been noted that the electronic properties of the Z-group strongly affect the equilibrium constant of the addition−fragmentation reaction and the apparent chain transfer constant. Depending upon the situation, this Z-group effect has been attributed to an effect on the stability of the RAFT-adduct radical and/or an effect on the reactivity (toward radical addition) of the RAFT agent. Thus, for example, RAFT agents that bear a strong electron-withdrawing Z-substituent (such as phenyl) fragment more slowly and have larger equilibrium constants as compared to those having less radical-stabilizing substituents (such as benzyl or methyl), and this has been attributed to the greater stability of the RAFT-adduct radical.[17,19,31,32] In contrast, RAFT agents bearing strong electron-donating substituents (such as alkoxy or amine groups) have considerably smaller equilibrium constants and chain transfer constants, and this has been attributed to the stabilizing effect of electron donation on the S=C bond of the thiocarbonyl compound.[18,22,24−28,33−35] Moreover, a semiempirical study of RAFT agents differing only in their Z-group reported a reasonable correlation between the calculated energy of the lowest unoccupied molecular orbital (LUMO) of the RAFT agent and the apparent chain transfer constant in polymerizations with a constant monomer,[22] which would indicate that the Z-substituent principally affects the activity of the RAFT agent.

However, even in the case of the alkoxy Z-substituents, the separation of substituent effects on the RAFT-adduct radical and RAFT agent is not clear-cut. For example, within a series of alkoxy-substituted RAFT agents (Z = O-Me, O-Et, O-*i*Pr, and O-*t*Bu), it was found that the fragmentation rates decreased, and the equilibrium constants thus increased, with the increasing donation ability of the alkoxy group (from O-Me to O-*t*Bu).[18] Had the principal effect of electron donation from the alkoxy group been to stabilize the S=C bond of the RAFT agent, one would have predicted an increase in stability of the agent within this series and thus a decrease in the equilibrium constant. To explain this result, it was suggested that, within the series, the stabilizing effect of the Z-substituent on the radical outweighed the concurrent stabilization of the thiocarbonyl compound, yielding the unexpected trend.[18] However, a study of the effects of substituents on radical stability in these reactions is required to confirm this result. Nonetheless, it appears that, while the Z-substituents affect the stability of both the thiocarbonyl compound and the RAFT-adduct radical, the relative importance of these effects vary considerably according to the system. This suggests that there may exist some potential for manipulating the stability (and hence reactivity) of the RAFT agent somewhat independently of the addition−fragmentation equilibrium constant, thereby allowing for the design of agents that are both reactive to radical addition but also fast to fragment and therefore nonretarding. To explore this possibility, a wider survey of the effects of more novel Z-substituents on the stability of the RAFT-adduct radical, and their concurrent effect on the overall addition−fragmentation enthalpy, would be desirable.

Another outstanding problem concerns the role of the R-group. In general, it has been noted that RAFT agents bearing an R-group that is either bulky and/or an effective radical stabilizing substituent have faster fragmentation rates and lower equilibrium constants. This is consistent with the notion that a bulky group favors fragmentation by destabilizing the breaking of the S−R bond of the RAFT-adduct, while a radical stabilizing substituent favors fragmentation by stabilizing the product $R^\bullet$ radical. However, both the apparent chain transfer constants and the equilibrium constants indicate that the fragmentation reaction is more favorable for the $C(CH_3)_2CN$ group, as compared to the cumyl group.[20,23,28,32,36] This is despite the fact that the cumyl group is larger than the $C(CH_3)_2CN$ group, and the corresponding cumyl radical is more stable;[9] thus, one would have predicted the opposite trend. It would seem that the R-group is exerting some additional (nonsteric) effect on the stability of the RAFT-adduct radical. This is surprising, given that radical stabilization energies for radicals of the form $^\bullet CH_2SR$ are relatively insensitive to the nature of R.[17] In this regard, it is worth noting that a recent computational study[17] indicated that the R-group effect on the β-scission enthalpy depended upon the nature of the Z-group, and the origin of these synergistic effects has yet to be determined.

Finally, it is of interest to explore the effect of the nonparticipating R′-group on the addition−fragmentation equilibrium. In semiempirical investigations[22,23] in which the calculated LUMO energies of RAFT agents were compared with their apparent chain transfer constants, it was concluded that the R′-group was not exerting an appreciable effect on the reactivity of the RAFT agent. This result has important practical applications for the computational modeling of RAFT polymerization, as it suggests that computational studies could replace the R′-group with a small substituent such as CH_3. This simplification greatly reduces the cost of the calculations, in turn allowing for larger R- and Z-groups to be studied and/or more accurate computational methods to be applied. Already, this approach has been used in the study of RAFT polymerization,[17−19] and although supported by the semiempirical investigations,[22,23] higher-level ab initio studies of the effect of the R′-substituent on the addition−fragmentation equilibrium would be desirable to confirm its validity.

To explore these outstanding issues, in the present work, we examine the effects of substituents on the addition−fragmentation equilibrium at a more fundamental level through the calculation of radical stabilization energies (RSEs) for the RAFT adduct radicals, $CH_3SC^\bullet(Z)SR$, and the corresponding leaving group radicals, $^\bullet R$. The RSEs were calculated for a variety of Z-substituents (Z = H, Cl, C≡CH, CH=CH$_2$, CN, CF$_3$, NH$_2$, CH$_3$, Ph, Bz, naphthyl, OCH$_3$, OCH$_2$CH$_3$, OCH(CH$_3$)$_2$, and OC(CH$_3$)$_3$) and R-substituents (R = CH$_2$CN, C(CH$_3$)$_2$CN, Bz, CH(Ph)CH$_3$, C(Ph)(CH$_3$)$_2$, CH$_2$COOCH$_3$, CH(COOCH$_3$)CH$_3$, CH$_2$OCOCH$_3$, and CH$_2$CH$_3$), chosen to model the RAFT agents used in typical polymerization systems, together with several novel RAFT agents featuring strong electron withdrawing or donating properties. By comparing the effects of these substituents on the stability of the reactant and product radicals, with those on the corresponding enthalpies of fragmentation, the effects of substituents on the stability of the RAFT-adduct radical and RAFT agent can be separated. In this way, this study hopes to provide a deeper understanding of the dramatic effect of substituents on the RAFT process and guidelines to assist in the optimization of the process for new monomers.

Measurement and Meaning of Radical Stability.

In the present work, we study the effects of substituents on radical stability in the RAFT process. However, the definition of radical stability is by no means straightforward because, strictly speaking, the stabilities of nonisomeric species of any kind are not directly comparable. In practice, one usually compares stabilities of nonisomeric carbon-centered radicals ($R^\bullet$) using the following reference reaction:[37]

$$R^\bullet + CH_3\text{-}H \rightarrow R\text{-}H + CH_3{}^\bullet \qquad (2)$$

The energy change of this reaction is known as the radical stabilization energy (RSE) of the radical $R^\bullet$. Such RSEs measure radical stability relative to a reference value of 0 for $^\bullet CH_3$, with positive values indicating that the $R^\bullet$ radical is more stable than $^\bullet CH_3$ and negative values indicating that it is less stable. When radical stabilities are defined in this manner, they generally yield intuitive results. For example, the $^\bullet CH_2Ph$ radical has an RSE of 58.9 kJ mol^{-1} [37] while the $^\bullet CH_2CH_2Ph$ radical has an RSE of only 10.6 kJ mol^{-1}.[19] The larger RSE for the former radical reflects the ability of the phenyl substituent to stabilize the unpaired electron through delocalization onto the aromatic ring, an effect that is inhibited in the $^\bullet CH_2CH_2Ph$ radical by the intervening CH$_2$ group. Not only can such RSEs be rationalized in chemical terms, but their values are often useful for rationalizing the effects of substituents on the kinetics and thermodynamics of chemical reactions. Thus, for example, the greater stability of the benzyl radical has been used to explain its lower reactivity (as compared with radicals having smaller RSEs, such as $^\bullet CH_3$) in radical addition reactions.[38]

Nonetheless, the use of a reference reaction introduces an element of arbitrariness into the definition of radical stability. Potential problems in the use of the reference eq 2 become clear when one considers that the energy change of this reaction is effectively the difference in the C−H bond dissociation energies of the respective closed-shell species, CH$_3$−H and R−H. One may well ask whether the RSE measures the difference in stability of the $R^\bullet$ and $^\bullet CH_3$ radicals or the difference in stability of the corresponding R−H and C−H bonds. This problem was recently highlighted for the case of the alkyl radicals $^\bullet CH_3$, $^\bullet CH_2CH_3$, $^\bullet CH(CH_3)_2$, and $^\bullet C(CH_3)_3$.[39−42] When defined using eq 2, the measured stabilities of these radicals increase in the following order: $^\bullet CH_3 < {}^\bullet CH_2CH_3 < {}^\bullet CH(CH_3)_2 < {}^\bullet C(CH_3)_3$, a trend that can be rationalized in terms of the stabilizing effect of the additional methyl substituents interacting by hyperconjugation with the radical center. In contrast, when radical stability is instead measured using the (equally arbitrary) reference eq 3, the reverse order of radical stabilities is obtained: $^\bullet CH_3 > {}^\bullet CH_2CH_3 > {}^\bullet CH(CH_3)_2 > {}^\bullet C(CH_3)_3$.

$$R^\bullet + CH_3{-}F \rightarrow R{-}F + CH_3{}^\bullet \qquad (3)$$

Table 1. Radical Stabilization Energies (RSEs) for Model RAFT-Adduct Radicals $CH_3SC^{\bullet}(Z)SCH_3$ and Corresponding Enthalpies for β-Scission ($CH_3SC^{\bullet}(Z)SCH_3 \rightarrow CH_3SC(Z){=}S + {}^{\bullet}CH_3$)[a]

$CH_3SC(Z)SCH_3$		RSEs (kJ mol^{-1})		ΔH β-scission (kJ mol^{-1})			
structure[b]	Z	RMP2	G3(MP2)-RAD	RMP2	G3(MP2)-RAD	RSE of $^{\bullet}CH_2Z$	stability[c] of $S{=}C(Z)SCH_3$
1	H	59.0	61.1	73.8	74.2	0	0.0
2	Cl	62.3	64.0	68.2	72.9	21.1[d]	29.9
3	$C{\equiv}CH$	109.1	105.7	117.3	114.4	52.6[d]	17.4
4	$CH{=}CH_2$	108.1	105.9	109.5	106.1	70.7[d]	39.1
5	CN	103.0	99.1	124.8	122.9	31.9[d]	−5.9
6	CF_3	60.7	62.8	86.3	92.0	−7.7[d]	−17.1
7	NH_2	78.9	78.9	33.2	35.7	44.2[d]	92.8
8	CH_3	57.0	59.9	62.3	64.2	14.1[d]	35.1
9	Ph	92.2	96.3	91.1	95.2	58.9[d]	41.2
10	Bz	60.8	65.0	69.4	72.3	10.6[e]	39.0
11	naphthyl	87.8		95.0			
12	OCH_3	55.3	58.5	23.5	29.2	31.0[d]	85.9
13	OCH_2CH_3	55.8	59.0	24.4	29.8	31.1[f]	86.8
14	$OCH(CH_3)_2$	60.5	63.2	27.8	33.4	34.8[f]	90.7
15	$OC(CH_3)_3$	56.4	59.0	32.0	37.1	34.8[f]	81.0

[a] RSEs and enthalpies (0 K) were calculated at both the RMP2/6-311+G(3df,2p) and the G3(MP2)-RAD levels of theory using B3-LYP/6-31G(d) optimized geometries and include scaled B3-LYP/6-31G(d) zero-point energy corrections. [b] See Figure 1. [c] Defined as the energy change (kJ mol^{-1}) of reaction 5, as calculated at the G3(MP2)-RAD level of theory. [d] G3(MP2)-RAD values (kJ mol^{-1}) from ref 37. [e] G3(MP2)-RAD (kJ mol^{-1}) value from ref 17. [f] Calculated using the G3(MP2)-RAD (kJ mol^{-1}) heats of formation published in ref 42.

This somewhat counter-intuitive result can be explained when it is noted that the electron-donating ability of the alkyl substituent increases from $^{\bullet}CH_3$ to $^{\bullet}C(CH_3)_3$, and this helps to stabilize the corresponding R-F bond through the increasing contribution of the charge-transfer configuration R^+F^-. Within this series, the increasing strength of the R-F bond dominates the concurrently increasing stabilities of the $R^{\bullet}$ radicals, leading to the observed reduction in the RSEs with increasing alkylation.

In summary, radical stability is a somewhat loosely defined concept, although one that has proven to be very successful in helping to rationalize the effects of substituents on the kinetics and thermodynamics of a range of chemical reactions. However, it is important that the reference reaction is chosen carefully, and in the present work, we measure radical stabilities via eq 2. As noted previously, when defined in this manner, the measured radical stabilities generally follow chemically intuitive trends. This probably reflects the minimal scope for steric and ionic substituent effects on the corresponding R−H and CH_3−H bonds. Nonetheless, it must be remembered that the RSEs can potentially include contributions from both the relative stabilities of both the $R^{\bullet}$ and $^{\bullet}CH_3$ radicals and also the C−H bonds in the corresponding closed shell compounds.

2. Computational Procedures

Radical stabilization energies (RSEs), as defined by eq 2, were calculated for the model RAFT-adduct radicals: $CH_3SC^{\bullet}(Z)SR$, with various combinations of Z = H, Cl, $C{\equiv}CH$, $CH{=}CH_2$, CN, CF_3, NH_2, CH_3, Ph, Bz, naphthyl, OCH_3, OCH_2CH_3, $OCH(CH_3)_2$, and $OC(CH_3)_3$ and R = CH_2CN, $C(CH_3)_2CN$, Bz, $CH(Ph)CH_3$, $C(Ph)(CH_3)_2$, CH_2COOCH_3, $CH(COOCH_3)CH_3$, CH_2OCOCH_3, and CH_2CH_3. To assist in the analysis of the results, the corresponding enthalpies for β-scission of the RAFT-adduct radicals ($CH_3SC^{\bullet}(Z)SR \rightarrow CH_3SC(Z){=}S + {}^{\bullet}R$ and $CH_3SC^{\bullet}(Z)SR \rightarrow {}^{\bullet}CH_3 + S{=}C(Z)SR$), together with the radical stabilization energies of $R^{\bullet}$ leaving groups, were also calculated. For some of the combinations of substituents, these latter quantities were taken directly from earlier computational studies,[17,18,20] although the relevant geometries are displayed in the figures and Supporting Information for the sake of completeness.

The RSEs and β-scission enthalpies were calculated at 0 K, using standard ab initio molecular orbital theory[43] and density functional theory[44] calculations, carried out using GAUSSIAN 98,[45] GAUSSIAN 03,[46] and MOLPRO 2000.6.[47] Unless noted otherwise, calculations on radicals were performed with an unrestricted wave function. In cases where a restricted-open-shell wave function was used, it is designated with an R prefix. The geometries of the reactants and products were optimized at the B3-LYP/6-31G(d) level of theory, while improved energies were calculated at the RMP2/6-311+G(3df,2p) and (where possible) G3(MP2)-RAD[48] levels of theory. It has previously been shown that G3(MP2)-RAD provides accurate absolute values and that RMP2/6-311+G(3df,2p) provides reasonable absolute values and excellent relative values for the enthalpies of radical addition to C=S double bonds.[49] Moreover, the G3(MP2)-RAD and RMP2/6-311+G(2df,p) levels of theory have also been shown to be suitable for studying the radical stabilization energies of carbon-centered radicals.[37] The performance of the RMP2/6-311+G(3df,2p) level of theory for the specific case of RAFT polymerization will be discussed in more detail below.

For each radical and thiocarbonyl compound considered, care was taken to ensure that the optimized structure was the global (rather than merely local) minimum energy structure, with extensive conformational searches at the HF/6-31G(d) level being performed. Having found the global minimum energy conformation, the geometry was then reoptimized at the B3-LYP/6-31G(d) level of theory. In calculating the radical stabilization energies, however, the minimum energy conformation of the radical was used as a basis for selecting the conformation of the corresponding alkane. The geometry of the alkane was then fully optimized to a (local) minimum energy structure within that conformation. In this way, the RSE is calculated for the most stable conformation of the RAFT-adduct radical (which is the species that is relevant to the polymerization system), but any possible contribution to the RSE arising from conformational changes between the radical and the alkane are minimized.

3. Results and Discussion

To examine the effect of the Z-substituent, the radical stabilization energies (RSEs) for the RAFT-adduct radicals $CH_3SC^{\bullet}(Z)SCH_3$, and the enthalpies for their β-scission reactions ($CH_3SC^{\bullet}(Z)SCH_3 \rightarrow CH_3SC(Z){=}S + {}^{\bullet}CH_3$), were calculated for the substituents Z = H, Cl, $C{\equiv}CH$, $CH{=}CH_2$, CN, CF_3, NH_2, CH_3, Ph, Bz, naphthyl, OCH_3, OCH_2CH_3, $OCH(CH_3)_2$, and $OC(CH_3)_3$ (see Table 1). The corresponding RSEs of the $^{\bullet}CH_2Z$ radicals, as calculated at the same level of theory in earlier studies,[17,37,42] are shown in Table 1 for purposes of comparison. To examine the effect of the R-substituent, the

Table 2. Radical Stabilization Energies (RSEs) for Model RAFT-Adduct Radicals $CH_3SC^{\bullet}(CH_3)SR$ and Corresponding Enthalpies for β-Scission of the R-Group ($CH_3SC^{\bullet}(CH_3)SR \rightarrow CH_3SC(CH_3){=}S + {}^{\bullet}R$) and Also the CH_3 Group ($CH_3SC^{\bullet}(CH_3)SR \rightarrow {}^{\bullet}CH_3 + S{=}C(CH_3)SR$)[a]

$CH_3SC(CH_3)SR$		RSEs (kJ mol^{-1})		β-scission of R (kJ mol^{-1})		β-scission of CH_3 (kJ mol^{-1})	
structure[b]	R	RMP2	G3(MP2)-RAD	RMP2	G3(MP2)-RAD	RMP2	G3(MP2)-RAD
8	CH_3	57.0	59.9	62.3	64.2	62.3	64.2
16	CH_2CN	60.1	62.7	42.1	39.7	80.4	81.0
17	$C(CH_3)_2CN$	75.9	78.7	40.1	33.9	88.2	90.5
18	Bz	60.7	63.5	47.5	34.2	74.9	75.9
19	$CH(CH_3)Ph$	67.0		51.9		77.7	
20	$C(CH_3)_2Ph$	71.7		51.7		92.6	
21	CH_2COOCH_3	56.8	61.1	59.0	58.1	76.4	78.1
22	$CH(CH_3)COOCH_3$	63.7	66.8	62.1	55.9	85.0	85.3
23	CH_2OCOCH_3	61.4	63.7	77.0	75.4	80.0	80.2
24	CH_2CH_3	61.3	63.7	71.0	69.9	66.7	68.0

[a] RSEs and enthalpies (0 K) were calculated at both the RMP2/6-311+G(3df,2p) and the G3(MP2)-RAD levels of theory using B3-LYP/6-31G(d) optimized geometries and include scaled B3-LYP/6-31G(d) zero-point energy corrections. [b] See Figure 2.

Table 3. Radical Stabilization Energies (RSEs) for ${}^{\bullet}R$ Leaving Group Radicals[a]

		RSEs (kJ mol^{-1})	
structure[b]	R	RMP2/6-311+G(3df,2p)	G3(MP2)-RAD
25	CH_3	0.0	0.0
26	CH_2CN	31.1	31.9
27	$C(CH_3)_2CN$	59.4	59.0
28	Bz	50.4	58.9
29	$CH(CH_3)Ph$	59.5	68.0
30	$C(CH_3)_2Ph$	62.4	70.3
31	CH_2COOCH_3	20.3	21.5
32	$CH(CH_3)COOCH_3$	40.4	41.3
33	CH_2OCOCH_3	17.6	17.9
34	CH_2CH_3	13.8	14.1

[a] RSEs and enthalpies (0 K) were calculated at both the RMP2/6-311+G(3df,2p) and the G3(MP2)-RAD levels of theory using B3-LYP/6-31G(d) optimized geometries and include scaled B3-LYP/6-31G(d) zero-point energy corrections. [b] See Figure 3.

Table 4. Radical Stabilization Energies (RSEs) for Model RAFT-Adduct Radicals $CH_3SC^{\bullet}(Z)SR$, and Corresponding Enthalpies for β-Scission of the R-Group ($CH_3SC^{\bullet}(Z)SR \rightarrow CH_3SC(Z){=}S + {}^{\bullet}R$)[a]

	$CH_3SC(Z)SR$			
structure[b]	Z	R	RSEs (kJ mol^{-1})	Δ*H* β-scission of R (kJ mol^{-1})
35	Bz	$C(CH_3)_2CN$	74.2	46.0
36	Ph	$C(CH_3)_2CN$	102.8	70.1
37	Bz	Bz	64.8	51.5
38	Ph	Bz	99.0	78.1
39	Ph	$CH(CH_3)Ph$	90.0	89.0
40	Ph	$C(CH_3)_2Ph$	105.8	81.2
41	Bz	CH_2COOCH_3	56.2	59.0
42	Ph	CH_2COOCH_3	89.2	81.8
43	OCH_3	CH_2OCOCH_3	47.4	30.4
44	OCH_2CH_3	CH_2OCOCH_3	49.5	33.6
45	$OCH(CH_3)_2$	CH_2OCOCH_3	56.7	35.9
46	$OC(CH_3)_3$	CH_2OCOCH_3	53.0	38.5

[a] RSEs and enthalpies (0 K) were calculated at the RMP2/6-311+G(3df,2p) level of theory using B3-LYP/6-31G(d) optimized geometries and include scaled B3-LYP/6-31G(d) zero-point energy corrections. [b] See Figure 4.

RSEs of the radicals $CH_3SC^{\bullet}(CH_3)SR$ (R = CH_2CN, $C(CH_3)_2CN$, Bz, $CH(Ph)CH_3$, $C(Ph)(CH_3)_2$, CH_2COOCH_3, $CH(COOCH_3)CH_3$, CH_2OCOCH_3, and CH_2CH_3) were calculated, together with the enthalpies for both possible β-scission reactions: $CH_3SC^{\bullet}(CH_3)SR \rightarrow CH_3SC(CH_3){=}S + {}^{\bullet}R$ and $CH_3SC^{\bullet}(CH_3)SR \rightarrow {}^{\bullet}CH_3 + S{=}C(CH_3)SR$ (see Table 2). To assist in the analysis of the results, the corresponding RSEs of the $R^{\bullet}$ leaving group radicals were also obtained (see Table 3). Finally, the effects of R and Z acting in combination on the RSEs and β-scission enthalpies were studied (see Table 4). The B3-LYP/6-31G(d) optimized geometries of all radicals in Tables 1−4 are provided in Figures 1−4, respectively, and complete geometries in the form of GAUSSIAN archive entries for all species are provided in the Supporting Information. It should be noted that a number of the β-scission enthalpies, and also some of the $R^{\bullet}$ RSEs, have already been reported elsewhere[17−20] but are reproduced here (at a consistent level of theory) to assist in the analysis of the RSEs of the RAFT-adduct radicals. In what follows, we discuss in turn the individual effects of Z- and R-substituents and conclude with an examination of the effects of the R- and Z-substituents acting in combination. Before proceeding to this analysis, however, we will begin with a brief comparison of the RMP2/6-311+G(3df,2p) and G3(MP2)-RAD levels of theory.

Effect of Level of Theory. Examining Tables 1−3, it can be seen that (where possible) the RSEs and β-scission enthalpies are reported at two levels of theory, RMP2/6-311+G(3df,2p) and G3(MP2)-RAD. The latter level of theory is a high-level composite procedure that has been shown to provide accurate absolute results (within ±5 kJ mol^{-1}) for the heats of formation of free radicals.[48] However, this method is computationally intensive, and its practical application is currently restricted to relatively small systems, such as the model RAFT-adduct radicals in which one of the R- or Z-substituents is a CH_3 group. To study larger (and more realistic) systems, the lower-level RMP2/6-311+G(3df,2p) method has been adopted. This choice was based on extensive assessment studies that indicate that this method can provide reasonable absolute values (typically within ±10 kJ mol^{-1}) and excellent relative values (within ±4 kJ mol^{-1}) for the kinetics and thermodynamics of radical addition to C=S bonds[49] and other radical reactions such as radical addition to alkenes[50] (i.e., the propagation step in free-radical polymerization) and hydrogen abstraction by carbon-centered radicals (i.e., chain transfer).[51] Moreover, the closely related RMP2/6-311+G(2df,p) method has been shown to perform well for the RSEs of carbon-centered radicals,[37] while RMP2/6-311+G(3df,2p) was shown to perform well for other types of relative bond dissociation energies.[42] It is also worth noting that these same studies indicated that the popular DFT method, B3-LYP, while providing excellent geometries and vibrational frequencies, often performs badly for the calculation of energy-related quantities, such as reaction enthalpies and RSEs, particularly for these polymerization-related radical reactions. While the use of the RMP2/6-311+G(3df,2p) method is already supported by these extensive

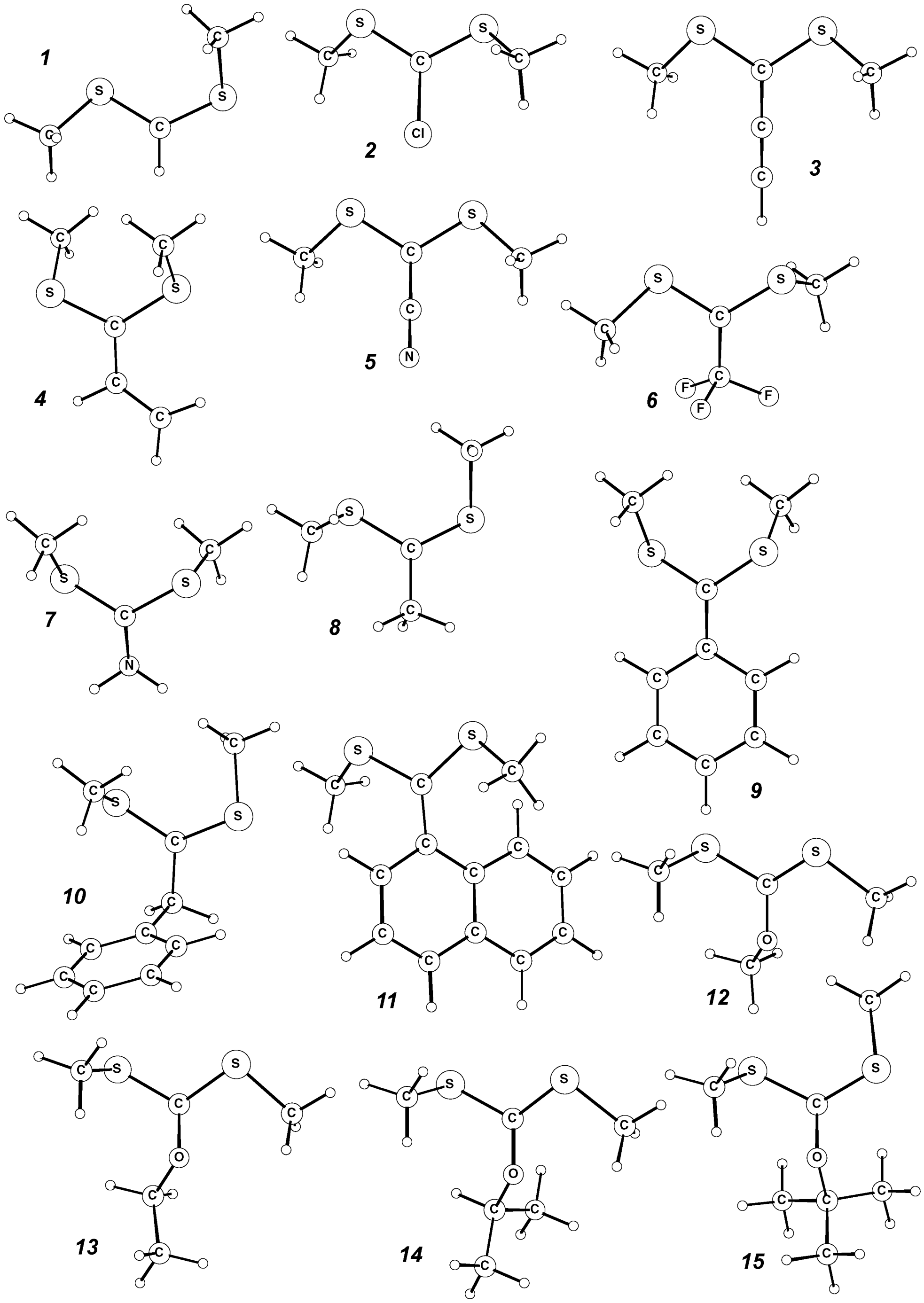


Figure 1. B3-LYP/6-31G(d) optimized geometries of the RAFT-adduct radicals in Table 1.

assessment studies, such studies have necessarily focused on small prototypical reactions, such as $^{\bullet}CH_3$ + $S{=}C(CH_3)_2$.[49] It is thus of interest to examine its performance in the more specific context of the RAFT polymerization process.

Examining first Table 1 (in which the RAFT-radicals differ only in their Z-group), we note that the RMP2/6-311+G(3df,2p) method generally provides excellent agreement with the considerably more expensive G3-(MP2)-RAD. The RSEs have a mean absolute deviation (MAD) of 2.7 kJ mol^{-1}, while the β-scission enthalpies have an MAD of 3.7 kJ mol^{-1}. Furthermore, within the alkoxy series, the error is almost constant—varying by just 0.6 kJ mol^{-1} as the Z-group is changed from O-Me to O-*t*-Bu. There is thus some indication that, within a series of similar substituents, the relative errors could be very low indeed. Turning our attention to Table 2, we note that the RMP2/6-311+G(3df,2p) method again shows excellent performance for the RSEs (MAD = 2.9 kJ mol^{-1}) and the β-scission enthalpies in which a constant $^{\bullet}CH_3$ radical is produced (MAD = 1.1 kJ mol^{-1}). However, the errors are considerably larger in the enthalpies of the β-scission reaction liberating the $^{\bullet}R$ radical (rather than $^{\bullet}CH_3$). The MAD for this series is 4.5 kJ mol^{-1}, and of greater concern, the maximum deviation is 13.3 kJ mol^{-1} (for the R = Bz case). The errors in this problem case are largely associated with the calculation of the delocalized benzyl radical. This is evident in Table 3, where it can be seen that the error in the RSE of this radical is also large (8.5 kJ mol^{-1}) as compared with the nonphenyl-substituted $R^{\bullet}$ radicals. At the UHF/6-31G(d) level of theory, the benzyl radical

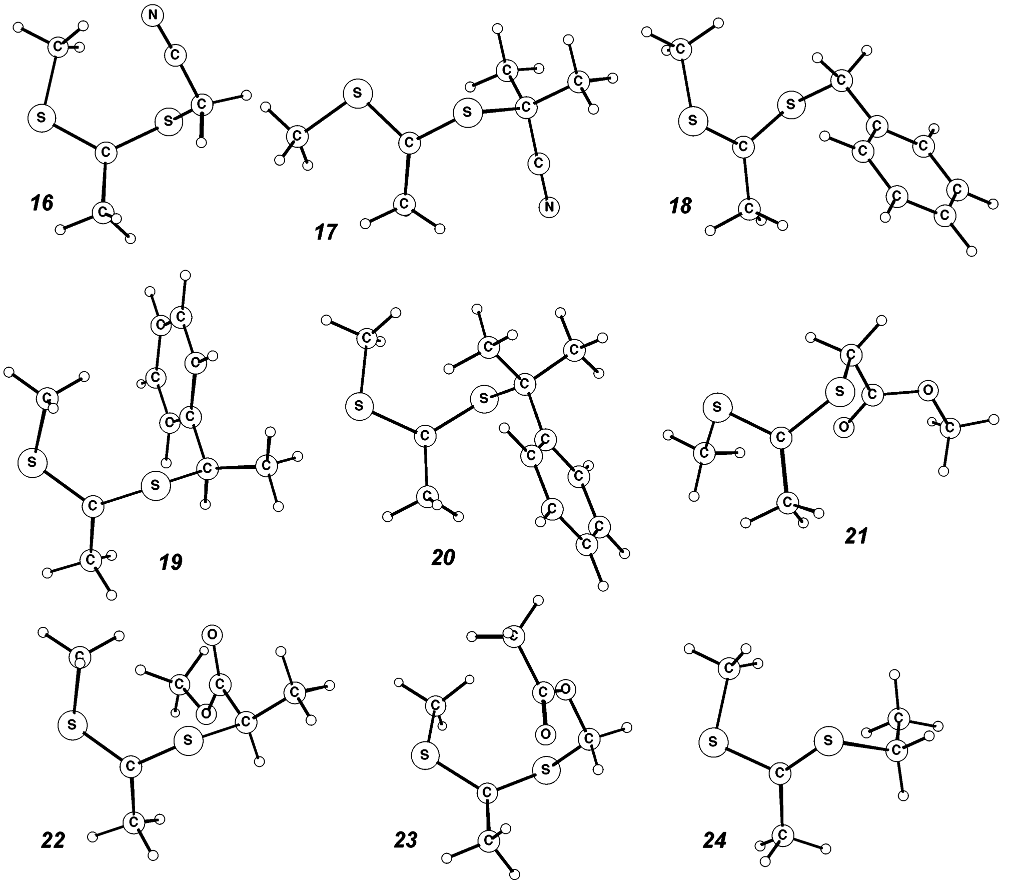


Figure 2. B3-LYP/6-31G(d) optimized geometries of the RAFT-adduct radicals in Table 2.

is highly spin-contaminated ($\langle S^2 \rangle = 1.39$), and this spin contamination, although unphysical, reflects the multireference character of the true wave function. At the RMP2/6-311+G(3df,2p) level of theory, the use of an RO-wave function addresses the spin-contamination problem; however, the use of this single-reference wave function enforces a larger degree of spin localization than might be expected in the real radical; hence, its stability is underestimated at the RMP2 level. From Table 3, it should also be noted that the other phenyl-substituted radicals, 1-phenylethyl and cumyl, have similarly large errors in their RSEs; hence, similar (large) errors might be expected in the enthalpies of the corresponding β-scission reactions involving these R$^•$ radicals. Unfortunately, these two reactions are currently too large for (practical) G3(MP2)-RAD calculations; however, such calculations should be feasible in the very near future.

To summarize, the RMP2/6-311+G(3df,2p) method performs well for the RSEs of the RAFT-adduct radicals and for the enthalpies of the β-scission reactions in which the constant $^•CH_3$ radical is liberated. However, larger errors are expected when the leaving group R$^•$ radical is varied, particularly if phenyl-substituted radicals are involved. It appears that the errors in these latter cases are largely associated with the calculation of the R$^•$ radical and might thus be expected to cancel from the relative values of the fragmentation enthalpy within a series featuring a common R$^•$ radical adding to RAFT agents differing in their Z-substituent. This suggests that reasonably accurate absolute values for the enthalpy of the RAFT reaction, R$^•$ + S=C(Z)SCH$_3$, may be obtainable using an ONIOM-type method[52] in

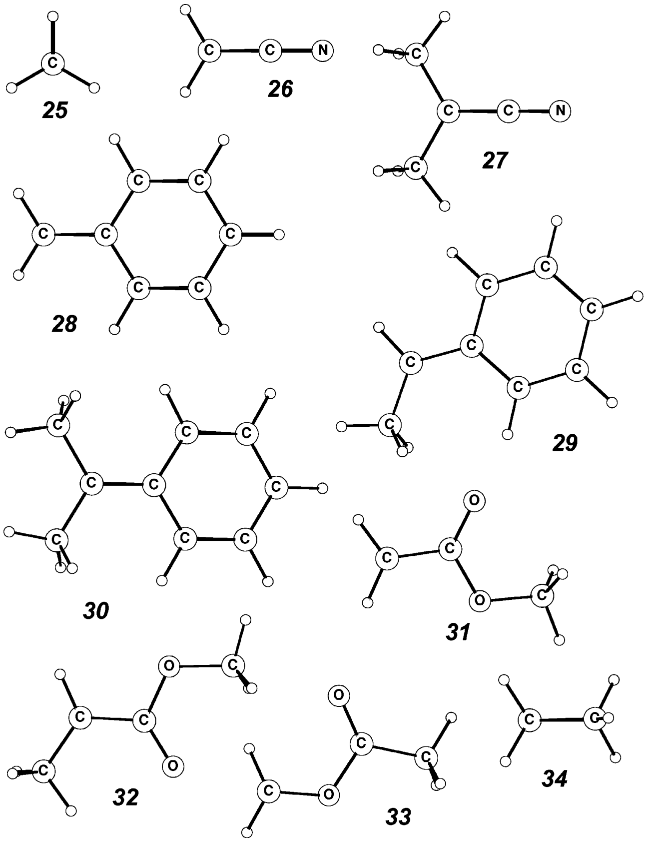


Figure 3. B3-LYP/6-31G(d) optimized geometries of the leaving group radicals in Table 3.

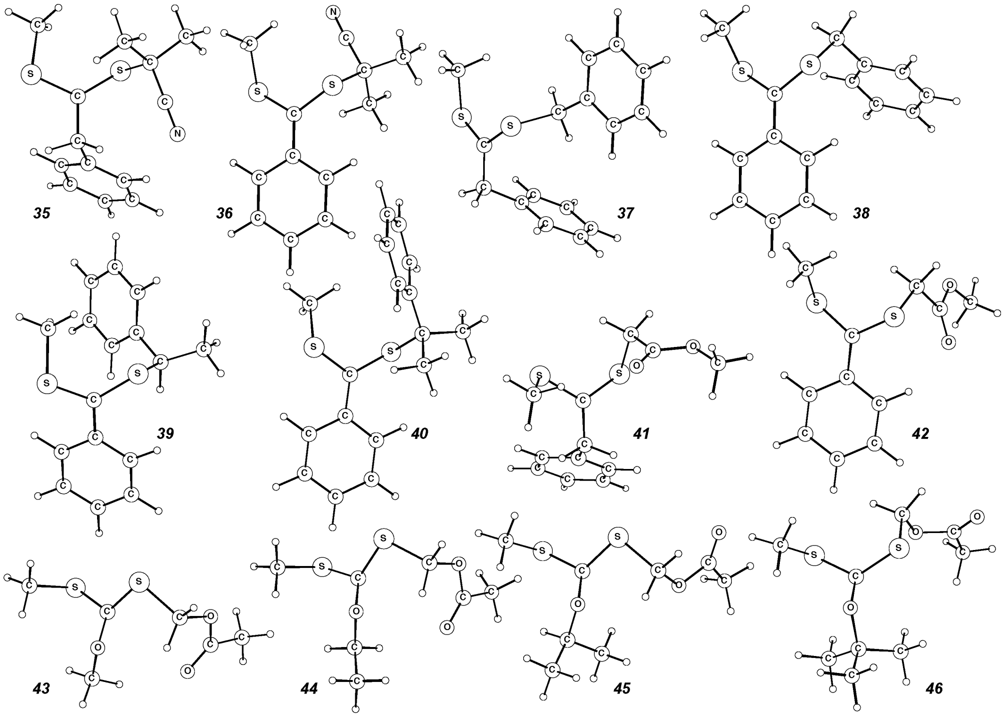


Figure 4. B3-LYP/6-31G(d) optimized geometries of the RAFT-adduct radicals in Table 4.

which the G3(MP2)-RAD enthalpies are calculated for the simplest Z = CH_3 case, and then the enthalpies for the larger Z-substituted systems are obtained at an approximate G3(MP2)-RAD level of theory. These latter values could be calculated by correcting the (exact) G3(MP2)-RAD enthalpy in the Z = CH_3 case for the Z-group effect, using calculations on both systems at the RMP2/6-311+G(3df,2p) level of theory, as shown in eq 4.

$$\Delta H(Z \neq CH_3) = \Delta H_{G3(MP2)-RAD}(Z = CH_3) + \Delta H_{RMP2}(Z \neq CH_3) - \Delta H_{RMP2}(Z = CH_3) \quad (4)$$

Effect of Z. Examining first the RSEs in Table 1 we note that, not unexpectedly, the unsaturated π-accepting Z-substituents (i.e., naphthyl, phenyl, CH=CH_2, C≡CH, and C≡N) greatly increase the stability of the RAFT-adduct radical as compared to Z = H. The strongest lone-pair donor substituent, NH_2, also stabilizes the RAFT-adduct radical, although not as significantly as the π-accepting Z-substituents. However, with these exceptions, the RSEs for the other $CH_3SC^{\bullet}(Z)SCH_3$ radicals fall into a surprisingly narrow range (55−62 kJ mol^{-1}). In contrast, the same substituents exert a much wider range of effects on the RSEs of $ZCH_2^{\bullet}$ radicals, the $ZCH_2^{\bullet}$ RSEs ranging from −7.7 kJ mol^{-1} (Z = CF_3) and 0 (Z = H) to 21.1 kJ mol^{-1} (Z = Cl) and 31.0 kJ mol^{-1} (Z = OCH_3).[37] It appears that the two SCH_3 substituents (which are strong radical stabilizing substituents through lone pair donation to the electron deficient center) are saturating the potential stabilization of the radical center and dominating the effect of the Z-substituent. Indeed, if we consider the simplest case, the $CH_3SC^{\bullet}(H)SCH_3$ radical, the RSE is 61.1 kJ mol^{-1}. In contrast, the radical stabilization effect of a single SCH_3 substituent on a carbon-centered radical (as measured via the RSE of the $^{\bullet}CH_2SCH_3$ radical[17]) is 40.7 kJ mol^{-1}. In other words, the second SCH_3 substituent effectively contributes only half of the stabilization effect that it would contribute in isolation.

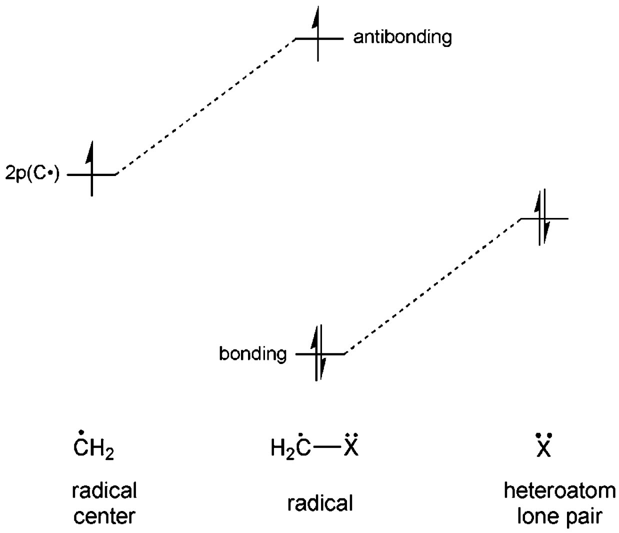


Figure 5. Orbital interaction diagram showing the three-electron interaction between the lone pair of a heteroatom and the unpaired electron at a carbon radical center.

To explain these results, it is helpful to consider the molecular orbital diagram in Figure 5,[37,53] which depicts the interaction between the formally singly occupied orbital corresponding to the unpaired electron at the radical center (2p($C^{\bullet}$)) and the lone pair of the heteroatom. Although a lone pair donor substituent, such as SCH_3, has a net stabilization effect on the radical center, the interaction results in the unpaired electron populating an antibonding orbital, higher in energy than 2p($C^{\bullet}$). As a result, the energy gap between the unpaired electron and a second lone pair donor is greater, and the stabilization effect of the second group is less. Furthermore, as a result of this second interaction, the unpaired electron is expected to reside in an orbital of even higher energy, and as a result, the interaction with a third donor would be expected to be even weaker (and possibly nonexistent). Applying these ideas to the RSEs in Table 1, we note that the only lone pair donor Z-substituent that exerts a large additional effect on the stability of the RAFT-adduct radicals in Table 1 is the NH_2 group. As seen from the corresponding $^{\bullet}CH_2Z$ RSEs, this substituent is a stronger radical stabilizing substituent than SCH_3; hence, it will form the principle interaction with the radical center. For this radical, the RSE is slightly less (by 6 kJ mol^{-1}) than the sum of the stabilization effect of an NH_2 substituent in isolation and a SCH_3 substituent in isolation, and this suggests that the third lone-pair-donor group (in this case SCH_3) makes a negligible contribution to the stability of the radical.

The radicals bearing the lone pair donor Z-substituents that are weaker radical stabilizers than SCH_3 (i.e., Cl and the O-alkyl series) generally have RSEs within ± 3 kJ mol^{-1} of that of the $CH_3SC^{\bullet}(H)SCH_3$ radical, indicating that the third lone pair donor substituent (in this case Z = Cl or O-alkyl) has only a small additional effect on the radical stability. In this regard, it is worth noting that the variation in radical stabilities within the O-alkyl series is relatively small. As explained in the Introduction, the fragmentation enthalpies within this series increase from Z = O-Me to O-*t*Bu, despite the fact that the increasing electron donation ability of the alkoxy group should have been expected to stabilize the thiocarbonyl product of fragmentation. It was suggested previously that this counterintuitive trend could be attributed to the concurrent increasing radical stabilization ability of the alkoxy group with its increasing electron donation ability.[18] However, the RSEs in Table 1 suggest that this is only partially correct. There is a small increase in radical stability from O-Me to O-*i*Pr, a trend that is mirrored in the $^{\bullet}CH_2Z$ RSEs (and the fragmentation enthalpies) and can be attributed to the increasing electron donation ability of the alkoxy group. However, unlike the $^{\bullet}CH_2Z$ radicals, there is a decrease in radical stability from O-*i*Pr to O-*t*Bu, as the bulkier *t*-Bu group forces the RAFT-adduct radical out of its preferred conformation (see Figure 1). As will be seen next, it is these steric factors, which serve to destabilize the thiocarbonyl compound more than the RAFT-adduct radical, that lead to the increased fragmentation enthalpy for the Z = O-*t*Bu system.

The remaining Z-substituents stabilize a radical through the interaction between the unpaired electron and the π^*-orbital (on the unsaturated π-accepting substituents, phenyl, naphthyl, $CH{=}CH_2$, $C{\equiv}CH$, and $C{\equiv}N$) or pseudo π^*-orbital (on the substituents that stabilize a radical by hyperconjugation: CH_3, Bz, CF_3). A molecular orbital diagram illustrating this stabilizing interaction for the unsaturated π-acceptor substituents is provided in Figure 6.[37,53] Before discussing the effects of these substituents on the stability of the RAFT-adduct radicals, it is worth noting a key geometric difference between these stabilizing interactions and those involving the lone pair donor substituents. When the RAFT-adduct radical is stabilized only by lone pair donor substituents, there is a significant puckering of the radical center. For instance, in the $CH_3SC^{\bullet}(H)SCH_3$ radical, the pyramidalization angle is 22.3°. Pyramidalization occurs because this lowers the energy of the $2p(C^{\bullet})$ orbital, thereby decreasing the energy gap between this orbital and that of the lone pair and thus facilitating a greater stabilizing interaction.[37,53] It is true that the puckering of the radical center also decreases the overlap between $2p(C^{\bullet})$ and the lone pair, which would serve to reduce the stabilizing interaction. Nonetheless, the large degree of pyramidalization that is observed is an optimum value that provides a compromise between these two competing effects.[37,53] In contrast, when unsaturated π-accepting substituents stabilize a radical, the preferred geometry at the radical center is planar because this maximizes the overlap between the $2p(C^{\bullet})$ orbital and the vacant π^*-orbital on the substituent.[37,53] Indeed, the RAFT-adduct radicals bearing the phenyl, $CH{=}CH_2$, $C{\equiv}CH$, and $C{\equiv}N$ substituents are planar (or virtually planar), despite the presence of the two SCH_3 groups. The radical bearing the naphthyl group also has a small pyramidalization angle (7.4°) but is not completely planar, due largely to steric crowding.

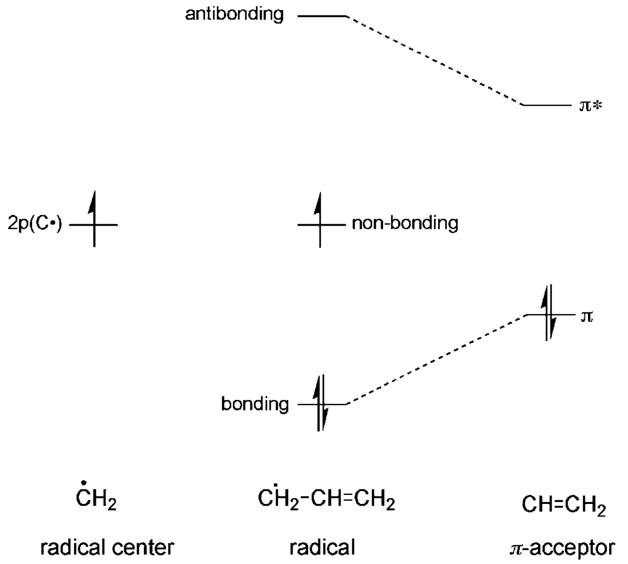


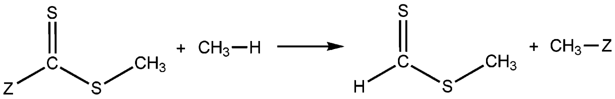
Figure 6. Orbital interaction diagram showing the three-electron interaction between the orbitals of the π acceptor group and the unpaired electron at a carbon radical center.

Applying these ideas to the RSEs in Table 1, we first note that the radicals bearing the unsaturated π-accepting substituents have large RSEs, but the RSEs are typically less than one would expect by considering the individual effects of the Z- and CH_3S-substituents. With the exception of the radical bearing the electron-withdrawing CN-substituent (for which captodative effects may be playing a role), the RSEs of the $CH_3SC^{\bullet}(Z)SCH_3$ radicals are less than the sum of the RSEs of the $^{\bullet}CH_2Z$ and $CH_3SC^{\bullet}(H)SCH_3$ radicals. As noted previously, the stabilizing effect of these π-accepting substituents is maximized when the radical center is planar; however, this planarization of the radical center reduces the stabilizing effect of the SCH_3 substituents (which is maximized for a pyramidal radical center). Indeed, the $CH_3SC^{\bullet}(Ph)SCH_3$ and $CH_3SC^{\bullet}(CH{=}CH_2)SCH_3$ radicals have RSEs that are slightly less than the sum of the stabilizing effect of the Z-substituent and a single SCH_3 substituent; the $CH_3SC^{\bullet}(C{\equiv}CH)SCH_3$ radical is 12.4 kJ mol^{-1} more but still less than the sum of the $^{\bullet}CH_2Z$ and $CH_3SC^{\bullet}(H)SCH_3$ radicals. The lower relative stabilization in the phenyl and ethylene substituted RAFT-adduct radicals, as compared with the ethynyl- and cyano-substituted species, is likely to be the result of steric factors. The $CH{\equiv}C$- and $N{\equiv}C$-substituents are both compact and linear and thus offer negligible steric hindrance to the two SCH_3 substituents, thereby allowing them to adopt the preferred conformation for interaction of the lone pairs with the radical center (see Figure 1). In contrast, in the CH_2=CH- and phenyl-substituted radicals, a conformational change is observed, with the bulkier Z-group forcing the SCH_3 groups to angle away, thereby decreasing the interaction of the sulfur lone pairs with the radical center. Nonetheless, despite the diminished role of the SCH_3 groups, the main observation from Table 1 is that the RSEs for all of the radicals bearing unsaturated π-accepting groups are very high, typically 40 kJ mol^{-1} higher than that of $CH_3SC^{\bullet}(H)SCH_3$.

In contrast to the unsaturated π-accepting substituents, the substituents that stabilize a radical through hyperconjugation have a negligible additional effect on the stability of the RAFT adduct radical. This is because the hyperconjugative effect is much weaker than the effect of lone pair donation from a SCH_3 group, and as a result, this effect dominates in the RAFT-adduct radicals. As noted previously, lone pair donation leads to puckering of the radical center, which in turn reduces the overlap required for delocalization of the unpaired electron into the π^*- or pseudo-π^*-orbitals of the Z-group. The pyramidalization angle in the $CH_3SC^{\bullet}(CH_3)SCH_3$ radical remains high (23.0°), confirming the negligible role of hyperconjugative stabilization in this system. Interestingly, the $CH_3SC^{\bullet}(CF_3)SCH_3$ and $CH_3SC^{\bullet}(CH_2Ph)SCH_3$ radicals are marginally more stable than $CH_3SC^{\bullet}(CH_3)SCH_3$ and have considerably smaller pyramidalization angles (3.6 and 9.2°, respectively), indicating that hyperconjugation may be playing a minor role. In the case of the benzyl radical, this planarization may be enforced by steric factors. Although such steric effects might be expected to destabilize (rather than stabilize) the radical, it must be remembered that the RSE measures the stability of the radical relative to its corresponding alkane (see Introduction). In this case, the steric effects may destabilize the corresponding alkane to a similar (or greater) extent and cancel from the RSE, with the RSE reflecting only the favorable effect of hyperconjugation on the stability of the radical. In the case of the CF_3 substituent, however, the results are more intriguing. Normally, this substituent destabilizes a radical, as the destabilizing effect of σ-withdrawal outweighs the hyperconjugative stabilizing interactions with the β-C-F bonds. However, in this case, the CF_3 substituent marginally stabilizes the radical, and it would appear that, in the presence of the SCH_3 substituents, the stabilizing effect of the hyperconjugation (which might be enhanced through a captodative interaction with the donor SCH_3 substituents) is sufficient to counter the negative effect of the σ-withdrawal. Nonetheless, the differences in radical stability are relatively small, and the main conclusion that can be drawn from Table 1 is that the substituents that stabilize a radical through weak hyperconjugative interactions have a negligible additional effect on the stability of the RAFT-adduct radical.

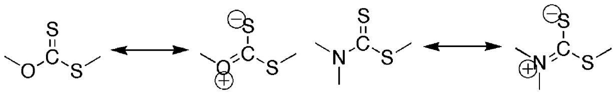
If we turn our attention to the β-scission enthalpies in Table 1, we find that, although radical stability plays a role in determining their values, other factors are also important. Generally, the trends in the fragmentation enthalpies follow the RSEs of the RAFT-adduct radicals. Thus, the RAFT-adduct radicals with large RSEs (i.e., Z = naphthyl, phenyl, CH=CH_2, C≡CH, and C≡N) have large β-scission enthalpies, as compared to those having small RSEs (i.e., Z = H, CH_3, Bz). However, there are some important exceptions to this. In particular, the radicals bearing the strongest lone pair donor Z-substituents have considerably smaller fragmentation enthalpies than should be expected on the basis of their RSEs. For example, the Z = NH_2 radical is considerably more stable (by 22 kJ mol^{-1}) than Z = CH_3 but has a considerably lower fragmentation enthalpy (by 29 kJ mol^{-1}). The Z = O-alkyl radicals also have very low fragmentation enthalpies when compared with Z = CH_3, despite having similar radical stabilities. In contrast to the lone pair donor substituents, the RAFT-adduct radicals bearing the strongest σ-acceptor substituents (Z = CF_3, CN) have considerably larger fragmentation enthalpies than should have been expected on the basis of their radical stabilities. In the case of Z = CF_3, the RAFT-adduct radical has a similar RSE to that for Z = H; however, the fragmentation enthalpy is 18 kJ mol^{-1} larger. In the case of Z = CN, the RAFT-adduct radical is slightly less stable than in the Z = CH=CH_2 system; however, the fragmentation enthalpy is larger by 17 kJ mol^{-1}.

It thus appears that the lone pair donor substituents stabilize the thiocarbonyl compounds (relative to Z = H), while the σ-acceptor substituents destabilize the thiocarbonyl compounds. This can be confirmed more quantitatively via the following isodesmic reaction:



(5)

Values of the enthalpy change for this reaction are included in Table 1, from which it can be seen that the reaction is strongly endothermic (by ca. 80−90 kJ mol^{-1}) for the RAFT agents with the strongest lone pair donor Z-substituents (i.e., the Z = NH_2, O-alkyl). These large positive values indicate that the thiocarbonyl compounds are considerably more stable than S=C(H)SCH_3. This adds further weight to the idea that the principal effect of these lone pair donor substituents is to help stabilize the S=C bond of the thiocarbonyl product of fragmentation, through the contribution of the resonance structures:[18,22,24−28,33−35]



(6)

In accordance with this notion, the charges on the sulfur of the S=C bond are strongly negative (ca. −0.12 to −0.15) for these RAFT agents.[54] The RAFT agents with Z-substituents that are weaker donors (such as CH_3, CH_2Ph, Ph, Cl, and CH=CH_2) are considerably less stable than the xanthate (i.e., Z = O-alkyl) and dithiocarbamate (i.e., Z = NH_2) RAFT agents but are still more stable than S=C(H)SCH_3 (typically by 30−40 kJ mol^{-1}). In these cases, the sulfur center of the S=C bond bears a small negative charge (ca. −0.03 in the case of Z = CH_3),[54] indicating that the resonance stabilization of the S=C bond plays a smaller role in these cases. Finally, the RAFT-agents with the strong σ-acceptor substituents (i.e., Z = CN, CF_3) have negative enthalpies, indicating that they are less stable than S=C(H)SCH_3, and in these cases, there is a small positive charge on the sulfur center (ca. 0.07−0.9).[54] It thus appears that σ-withdrawal actively destabilizes the C=S bonds of the thiocarbonyl compounds and that σ-acceptor substituents might thus be used to enhance the reactivity of the thiocarbonyl compounds for polymerizations involving relatively unreactive propagating radicals.

Although the stability of the RAFT agents appears largely to be governed by the electronegativity of the Z-group, steric factors also play a role. In particular, within the xanthate series, the stability of the RAFT agent increases from Z = O-Me to O-*i*Pr in accordance with the increasing electron-donating ability of the O-alkyl group but then decreases for the bulkiest Z-substituent, Z = O-*t*Bu. This is despite the fact that this substituent is the strongest electron donor, and the S center of the S=C bond bears the largest negative charge for this system (the charges on sulfur are −0.126, −0.129, −0.141, and −0.142 for O-Me to O-*t*Bu, respectively[54]). As explained previously, it is this steric destabilization of the thiocarbonyl compound that is responsible for this system having the largest fragmentation enthalpy within the alkoxy series. Steric factors may also explain why the fragmentation enthalpy is greater for the Z = naphthyl substituent, as compared with the Z = phenyl substituent, despite the fact that the RAFT-adduct radical is more stable in the latter case. It seems that, in general, the steric effect of bulky Z-groups is more pronounced in the RAFT agent than in the RAFT-adduct radical; thus, the fragmentation enthalpies for RAFT-adduct radicals bearing bulky Z-groups might be expected to be smaller than should be predicted on the basis of electronic factors alone.

In summary, the RAFT-adduct radicals $CH_3SC^{\bullet}(Z)SCH_3$ are generally very stable due to the presence of two lone pair donor SCH_3 substituents. This stability is further enhanced by Z-substituents that are unsaturated π-acceptors, and in this regard, we predict that a RAFT agent with a Z = CN substituent should be extremely slow to fragment and might thus be suitable in polymerizations featuring extremely stable propagating radicals. In contrast, lone pair donor Z-substituents, which normally stabilize a radical, show a negligible additional effect on radical stability, unless their stabilization effect is very large to begin with (as in the case of NH_2). The steric effects of the Z-substituent can also have an effect on the stability of the RAFT-adduct radical, with the bulkier substituents inducing conformational changes that interfere with the stabilizing effects of the SCH_3 substituents. Nonetheless, these effects appear to be relatively minor, and Z-substituents that significantly destabilize the RAFT-adduct radical, relative to Z = CH_3, have not as yet been identified. The effects of substituents on the stability of the RAFT agents are qualitatively different. In general, RAFT agents are strongly stabilized by electron donating substituents (such as OCH_3 or NH_2) and destabilized by σ-withdrawing substituents (such as CN and CF_3). Moreover, steric effects appear to be more pronounced in the RAFT agents than in the corresponding RAFT-adduct radicals.

Effect of R. Examining the RSEs in Table 2, we note that the effect of the R-group on the stabilities of the RAFT-adduct radicals is much smaller than the effect of the Z-substituent. In particular, if we consider the monosubstituted R-groups (CH_2CN, CH_2Ph, CH_2COOCH_3, CH_2OCOCH_3, and CH_2CH_3), the RSEs range from 61.1 to 63.7 kJ mol^{-1} and are very close to that of the corresponding R = CH_3 system (59.9 kJ mol^{-1}). This small variation occurs although the electronic properties of the R-substituents vary quite considerably. The minimal effect of these R-substituents on the stability of the RAFT-adduct radicals, as compared with the effects of substituents in the Z-position, can in part be explained by the physical location of the substituent. In contrast to the Z-group, the R-group is not directly attached to the radical center but is instead insulated by an intervening sulfur atom. Moreover, the substituent that is being varied within the R-group is not attached to the sulfur but instead to an intervening carbon atom. As a result, there is no possibility for conjugation between π-systems of the substituents on the R-group and the unpaired electron of the radical center, and other types of direct orbital interactions between the R-group and the unpaired electron should either be weak or totally inhibited.

It is possible for the R-group to exert an indirect effect on the stability of the RAFT-adduct radical by modifying the electron donation ability of the SR group. In particular, one would expect a strong π-acceptor substituent such as CN to reduce the stability of the radical by weakening the lone pair donation from the sulfur of the SR group. Indeed, in the simpler X-$CH_2SCH_2^{\bullet}$ system, the inclusion of X = CN reduces the RSE by 7.8 kJ mol^{-1}, relative to X = H.[29] However, in the RAFT-adduct radical, X-$CH_2SC^{\bullet}(CH_3)SCH_3$, the same substitution marginally stabilizes the radical (by 2.8 kJ mol^{-1}). In both cases, the preferred conformation of the radical features the CN substituent in the gauche position with respect to the radical center (i.e., anti to a lone pair on the sulfur). Since this position, which maximizes the orbital interactions between the CN substituent and the sulfur lone pair, is favored despite the steric preference for the anti conformation, one would conclude that the CN substituent is interacting with the sulfur lone pair in both cases.

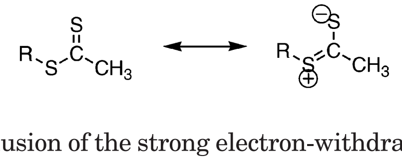
To explain the diminished effect of this interaction on the stability of the RAFT-adduct radical, we recall that, in radicals such as $CH_3SC^{\bullet}(CH_3)SCH_3$, the stabilizing effect of the two lone pair donor SCH_3 substituents is already considerably less than the sum of their individual effects. This is because the interaction between the radical center and the lone pair of the sulfur atom, although stabilizing, results in the unpaired electron populating an antibonding orbital, higher in energy than $2p(C^{\bullet})$. This increases the energy gap between the unpaired electron and the lone pair of a second donor substituent, thereby decreasing the possibility of a stabilizing interaction between them. Since the extent to which the second interaction is weakened depends on the strength of the first interaction, there is considerable scope within the $CH_3SC^{\bullet}(CH_3)SR$ radicals for the stabilizing effect of the SCH_3 group to decrease or increase to compensate for a stronger or weaker stabilization by the SR group. In other words, it appears that the second SCH_3 substituent is buffering the effect of the SR group on the radical stability. In fact, the reduced stabilization from the sulfur lone pair of the SR group is also buffered by a compensating homo-anomeric interaction between the unpaired electron and pseudo-π^* orbital of the S−R bond. These orbital interactions, which have important implications for the radical geometry and the strength of the S−R bond, will be discussed in more detail below.

Although the monosubstituted R-groups do not appear to affect the stability of the RAFT-adduct radicals, the RSEs increase significantly with the inclusion of additional methyl substituents in the R-group. Thus, for example, the RSE of the disubstituted $CH_3SC^{\bullet}(CH_3)S-CH(COOCH_3)CH_3$ radical is 5.7 kJ mol^{-1} higher than that of the corresponding monosubstituted $CH_3SC^{\bullet}(CH_3)S-CH_2COOCH_3$ radical; while that of the trisubstituted $CH_3SC^{\bullet}(CH_3)S-C(CH_3)_2CN$ radical is 16 kJ mol^{-1} higher than that of the corresponding monosubstituted radical $CH_3SC^{\bullet}(CH_3)S-CH_2CN$. Moreover, in the $CH_3SC^{\bullet}(CH_3)S-CXY(Ph)$ series, the inclusion of the first methyl (i.e., $CH_3SC^{\bullet}(CH_3)S-CH(CH_3)Ph$), stabilizes the radical by 6.3 kJ mol^{-1} (relative to $CH_3SC^{\bullet}(CH_3)S-CH_2Ph$), while the inclusion of the second methyl substituent (i.e., $CH_3SC^{\bullet}(CH_3)S-C(CH_3)_2Ph$) adds a further 4.7 kJ mol^{-1} to the RSE. This methyl substituent effect in the R-group appears to be relatively systematic, independent of the other substituents in the R-group. Moreover, this substituent effect occurs despite the fact that, due to the presence of the second SCH_3 substituent, the monosubstituted R-groups have a negligible effect on the overall radical stability. On this basis, it would appear the effect of the additional methyl substituents on radical stability is largely steric in origin. However, what is intriguing is that the radical appears to become more (rather than less) stable as the R-group becomes more bulky.

To understand this unusual effect, we recall from the Introduction that the RSE measures the stability of a radical $X^{\bullet}$, relative to the corresponding closed-shell compound, $X-H$. Thus, the increase in the RSEs of the RAFT-adduct radicals $R-SC^{\bullet}(CH_3)SCH_3$ with increasing bulk of the R-group, may reflect an increase in the stability of the radical and/or a decrease in the stability of the corresponding closed-shell compound (i.e., $R-SCH(CH_3)SCH_3$). In the present case, it seems likely that the inclusion of the additional methyl substituents in the R-group is actually destabilizing the reference alkane, rather than stabilizing the RAFT-adduct radical. In support of this notion, we note that in the $R-SCH_2^{\bullet}$ radicals, the inclusion of additional CH_3 groups does not have a significant effect on radical stability; the RSEs for the series R = CH_3, CH_2CH_3, $CH(CH_3)_2$, and $C(CH_3)_3$ being 40.7, 41.8, 41.6, and 41.4 kJ mol^{-1}, respectively. As noted previously, simple molecular orbital arguments suggest that the electronic effects are expected to be larger in the $R-SCH_2^{\bullet}$ radicals, as compared with the RAFT-adduct radicals, and for the monosubstituted R-groups this is indeed the case. Hence, the absence of significant methyl substituent effects in the $R-SCH_2^{\bullet}$ RSEs suggests that the methyl substituent effects in the RAFT systems are not electronic in origin. In contrast, the steric effects in the closed-shell species are expected to be smaller in the $R-SCH_3$ systems, as compared with the more crowded $R-SCH(CH_3)SCH_3$ systems. Hence, the absence of a significant methyl-substituent effect in the $R-SCH_2^{\bullet}$-RSEs is consistent with a steric origin for the substituent effects in the RAFT RSEs. In conclusion, based on both molecular orbital arguments, and the results for the monosubstituted RAFT-radicals and the $R-SCH_2^{\bullet}$ systems, it appears that the R-group does not have a significant effect on the inherent stability of the RAFT-adduct radical. Instead, the trends in the RSEs for the RAFT radicals are likely to be reflecting the steric destabilization of the reference alkane, as the R-group becomes more bulky.

Although the trends in the RSEs do not appear to be associated with the stability of the RAFT-adduct radical, similar trends are nonetheless observed in the enthalpies of the β-scission reactions in which the $^{\bullet}CH_3$ radical is produced: $CH_3SC^{\bullet}(CH_3)SR \rightarrow {}^{\bullet}CH_3 + S{=}C(CH_3)SR$. We recall from Table 1 that the enthalpy for R = CH_3 is 64.2 kJ mol^{-1}. In contrast, the enthalpies in Table 2 for the monosubstituted R-groups are higher (68.0−80.2 kJ mol^{-1}), and further increases (of 10−20 kJ mol^{-1}) are seen when additional methyl substituents are included in the R-group. As with the RSEs, the trends in the enthalpies reflect the relative stability of the RAFT-adduct radical and a related closed-shell species, in this case the thiocarbonyl compound. The increase in fragmentation enthalpy with the increasing substitution of the R-group may reflect an increase in the radical stability but may also indicate a decrease in the stability of the thiocarbonyl compound. As argued previously, the evidence suggests that the R-group is not significantly affecting the stability of the RAFT-adduct radical; thus, it would appear that the bulkier R-groups are instead destabilizing the thiocarbonyl compounds.

These substituent effects on the stability of the thiocarbonyl compounds are likely to be the result of both steric and electronic factors. From an electronic viewpoint, it must be remembered that the SR group is an electron donor that contributes to the stability of the thiocarbonyl compound via the contribution of the resonance structures:



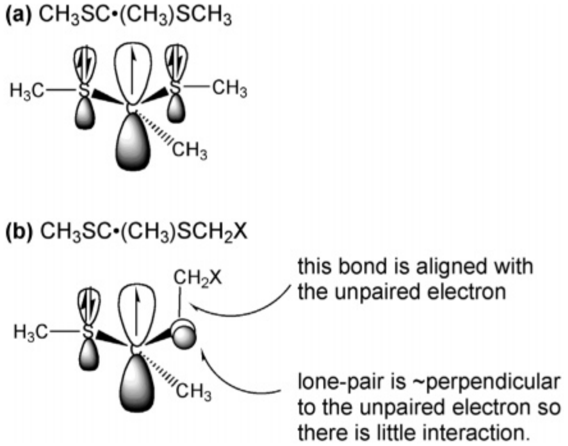
(7)

The inclusion of the strong electron-withdrawing CH_2CN group in the R-position reduces its electron donating ability, leading to a reduced stability and hence a larger fragmentation enthalpy (as compared with, for example, the sterically similar CH_2CH_3 R-group). In support of this, we note that the charge on the sulfur center of the S=C bond is slightly negative (−0.03) in the R = CH_3 or CH_2CH_3 systems but zero in the R = CH_2CN system.[54] The inclusion of larger monosubstituted R-groups (such as CH_2Ph, CH_2COOCH_3, and CH_2OCOCH_3) or additional methyl substituents in the R-group also increases the fragmentation enthalpy relative to R = CH_3 or CH_2CH_3. As in the case of the RSEs, these effects are likely to be steric in origin with the additional substituents destabilizing the closed-shell compounds, more than the radicals. The steric effects are expected to be larger in the thiocarbonyl compounds (as compared with the radicals) because the relatively rigid S=C−S π-system is less able to distort to reduce the through-space nonbonding interactions.

The present results thus indicate that the R-group does affect the stability of the RAFT agent; hence, it seems that it is necessary to model the effects of this substituent using realistic chemical models. As seen in the present work, the replacement of the R′ = CH_3 by more realistic substituents leads to an increase in the fragmentation enthalpy by as much as 25 kJ mol^{-1}. As a result, recent computational studies[17−20,55] of RAFT in which the R′ group (in the more general RAFT reaction, $R^{\bullet} + S{=}C(Z)SR' \rightarrow RSC^{\bullet}(Z)SR'$) was modeled using a CH_3 substituent may be underestimating the equilibrium constant for the addition−fragmentation reaction and overestimating the fragmentation rates. It should be noted, however, that these errors serve only to reinforce the conclusion from these previous studies[17,19,20,55] that slow fragmentation of the RAFT-adduct radical is leading to rate retardation in certain cumyl dithiobenzoate mediated RAFT systems. Nonetheless, for the more general problem of predicting accurate kinetic and thermodynamic parameters in RAFT polymerization, it is clear that more sophisticated chemical models are necessary. Although realistic (and hence large) R′ groups would be desirable, this must be balanced against the requirement of minimizing the size of the system so as to allow for the use of accurate levels of theory. The present results suggest that, except for highly electronegative substituents (such as CN), the decreased stability of the RAFT agents is largely associated with the steric bulk of the R′-group. On this basis, it appears that models such as R′ = CH_2CH_3 or $CH_2CH_2CH_3$ (for monosubstituted R′ groups) or R′ = $CH(CH_3)_2$ (for disubstituted R′ groups) may be sufficient in the majority of cases. Further calculations to evaluate the accuracy of such simplified chemical models in specific polymerization systems are currently underway.

Turning our attention to the fragmentation reactions in which the $R^\bullet$ radical is liberated (i.e., $CH_3SC^\bullet(CH_3)SR \rightarrow CH_3SC(CH_3){=}S + R^\bullet$), we note that the effect of the R-group on the reaction enthalpies is now qualitatively different. In these reactions, any steric interactions between the R-group and the rest of the radical are relieved by the fragmentation reaction; hence, the increasing steric bulk of R should help to lower (rather than increase) ΔH. Moreover, since the product radical $R^\bullet$ is now varied, the stability of this radical should also contribute to the trends in ΔH. Examining Table 2, we note that in general terms, the R-groups that are larger and/or stabilize radicals more have lower fragmentation enthalpies. Thus, the lowest fragmentation enthalpies occur for the R-groups bearing the radical stabilizing CN or Ph substituents, and in most cases, the fragmentation enthalpies decrease with the increasing substitution of the R-group. However, it is also clear that other factors are contributing to the fragmentation enthalpies. For example, the fragmentation enthalpies for the CN-substituted leaving groups appear to be lower than they should be on the basis of their steric and radical stabilizing properties, a trend that has been noted previously.[20,23,28,32,36] Moreover, in the $CH_3SC^\bullet(CH_3)S-CXY(Ph)$ series, the inclusion of additional methyl substituents marginally increases the fragmentation enthalpy, despite the fact that (a) the R-group becomes more bulky thereby increasing steric interactions in the RAFT-adduct radical and (b) $R^\bullet$ is a more stable leaving group radical. Normally, these factors would be expected to lead to a lowering in the reaction enthalpy.

To explain these seemingly anomalous trends, we need to examine the effect of the R-group on the RAFT-adduct in more detail. Although the monosubstituted R-substituents do not appear to affect the overall stability of the RAFT-adduct radical, they do have a profound effect on the geometry of the radical and the strength of the S−R bond. Examining first the geometries, we note that in the $CH_3SC^\bullet(CH_3)SCH_3$ radical (**1**), the two sulfur lone pairs contribute almost equally to the stabilization of the unpaired electron, and this is reflected in the minimum energy conformation of the radical. In this conformation, the two $S-CH_3$ bonds are distorted by similar amounts (47.1 and 34.6°) from the $SC^\bullet S$ plane; thus, both sulfur lone pairs can overlap with the unpaired electron (see Figure 7a). Of course, the overlap in each case is by no means perfect, as the requirement for maximum overlap is balanced by other factors (such as steric considerations); indeed, as explained previously, neither substituent contributes the same stabilizing effect it would have contributed in isolation. In the $CH_3SC^\bullet(CH_3)SCH_2CN$ radical (**16**), the p-type lone pair of the sulfur atom in the CH_3S group contributes a greater stabilizing interaction with the unpaired electron than the sulfur lone pair on the SCH_2CN group, and this results in a very different conformational arrangement. In particular, the $CH_3SC^\bullet(CH_3)S$ fragment of the radical is virtually planar and in a cis conformation, while the S−C bond of $S-CH_2CN$ group is angled at 73.4° to the $SC^\bullet S$ plane. This conformation maximizes the overlap of the CH_3S sulfur lone pair with the unpaired electron at the expense of the SCH_2CN lone pair (see Figure 7b), reflecting the increased stabilization from the former lone pair and the reduced role of the latter.


(a) $CH_3SC{\bullet}(CH_3)SCH_3$

(b) $CH_3SC{\bullet}(CH_3)SCH_2X$

Figure 7. Effect of the R group in $CH_3SC{\cdot}(CH_3)SR$ radicals.

The conformations of the radicals bearing the other monosubstituted R-groups (i.e., R = CH_2X in $CH_3SC^\bullet(CH_3)SR$) generally fall into the broad spectrum covered by the contrasting X = H and X = CN cases. For instance, the interaction between the X = CH_3 substituent and the sulfur lone pair is weak, and as a result, in this radical (**24**) both the $S-CH_3$ and the $S-CH_2X$ bonds are distorted from the $SC^\bullet S$ plane by similar amounts (42.9 and 38.8°). In other words, the conformation of the radical resembles that of the X = H case. In contrast, the X = Ph substituent can act as both a π-acceptor and a π-donor and can thus interfere weakly with the donation ability of the sulfur atom. The conformation of this radical (**18**) is thus intermediate to those of the X = H and X = CN systems, with the $S-CH_2X$ bond is orientated at 63.7° to the $SC^\bullet S$ plane and the $S-CH_3$ bond at 28.8°. An intermediate conformation is also observed for the X = $OCOCH_3$ substituted radical (**23**), with the $S-CH_2X$ and $S-CH_3$ bonds making angles with the $SC^\bullet S$ plane of 73.4 and 14.7°, respectively. It should be noted that, although normally regarded as a net electron donor, the X = $OCOCH_3$ substituent acts as an electron acceptor in this context, reducing the electron donation ability of the adjacent sulfur lone pair. This is because the X-group is not conjugated with the sulfur atom, and as a result, its σ-accepting properties outweigh its π-donation properties. The radical bearing the X = $COOCH_3$ (**21**) group shows somewhat unusual behavior. The X = $COOCH_3$ substituent is a moderate electron acceptor, and in this radical (**21**), the $S-CH_2X$ bond is oriented at 53.1° to the $SC^\bullet S$ plane, intermediate to the X = CN and X = H cases. However, in contrast to the other electron accepting X-groups, the $S-CH_3$

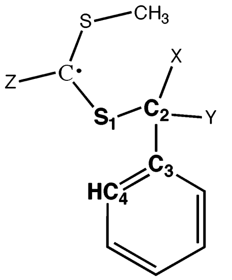
bond in this radical is also significantly distorted from planarity (by 46.7°). This distortion occurs as the result of intramolecular H-bonding. As the S−CH_3 bond angle with the SC•S plane increases, the distance between the carbonyl oxygen and a hydrogen atom on the S−CH_3 group diminishes (to 2.593 Å), resulting in an increased H-bonding interaction that counteracts the decreased stabilization of the unpaired electron.

These conformational changes to the RAFT-adduct radical $CH_3SC^•(CH_3)S{-}CH_2X$ when electron withdrawing X-groups are introduced in turn affect the strength of the S−CH_2X bond. Returning to Figure 7, we recall that, in the R = CH_3 case (A), both sulfur lone pairs overlap with the unpaired electron, reflecting their approximately equal roles in stabilizing the radical center. In case B, when an electron withdrawing X-group is introduced, the electron donating ability of the adjacent sulfur atom is diminished, and this leads to a conformational change in which the 2p(S) lone pair of the S−CH_2X sulfur substituent is almost perpendicular to 2p(C•) and has little or no overlap with these orbitals. From Figure 7B, it is seen that, in this geometry, the S−CH_2X bond is almost antiperiplanar with the 2p(C•) orbital of the radical center. The stability of this arrangement can be explained in terms of a homo-anomeric type interaction.[56] In molecular orbital terms, the electron withdrawing X groups (CN, Ph, ...) have the effect of lowering the energy of the pseudo-π^*-orbital of the S−CH_2X bond. At the same time, the increased donation of the lone pair of the SCH_3 group raises the energy of the unpaired electron sufficiently for it to interact with the pseudo-π^*-orbital of the S−CH_2X bond. As a result, a weak captodative-type stabilization is possible, in which the SCH_3 group acts as the electron donor, and the pseudo-π^*-orbital of the S−CH_2X bond acts as the π-acceptor. This homo-anomeric interaction contributes to the preference for the perpendicular geometry, as depicted in Figure 7B. Although stabilizing, this interaction comes at the expense of the lone pair donation from SCH_2X, and the net effect on the overall radical stability is negligible in the monosubstituted systems. However, the introduction of electron density into the (antibonding) pseudo-π^*-orbital of the S−CH_2X bond weakens this bond. This is clearly evident in the respective S−CH_2X and S−CH_3 bond lengths. For instance, in the X = CN substituted radical, the S−CH_2-CN bond length is 1.891 Å, whereas the opposite S−CH_3 bond is only 1.823 Å. In contrast, in the X = CH_3 case, the homo-anomeric effect is much weaker and the respective S−CH_2X and S−CH_3 bond lengths are much closer (at 1.849 and 1.831 Å). The X = Ph radical shows intermediate behavior, and in this case the bond lengths are 1.886 and 1.828 Å.

Applying these ideas to the fragmentation enthalpies, we first note that the CH_2CN group should fragment more easily than might be predicted on the basis of radical stabilization and steric arguments. The CH_2Ph group should also fragment easily but, if all other factors were equal, should have a higher fragmentation enthalpy than the CH_2CN group. Of course, all other factors are not equal as the $^•CH_2Ph$ radical is considerably more stable than $^•CH_2CN$, the respective RSEs being 58.9 and 31.9 kJ mol^{-1} (see Table 3). Nonetheless, the fragmentation enthalpy for the R = CH_2CN system is only 5.5 kJ mol^{-1} higher than that of the R = CH_2Ph system, despite the product R• radical being 30 kJ mol^{-1} less stable in the former case. It should also be noted that, under the same reasoning, the CH_3 group should fragment least easily from the $CH_3SC^•(CH_3)SCH_2CN$ radical, more easily from the $CH_3SC^•(CH_3)SCH_2Ph$ radical and most easily from $CH_3SC^•(CH_3)SCH_2CH_3$, and this is indeed the case. This relative strengthening of the CH_3−S bond, at the expense of the S−R bond, may thus contribute to the trends in the fragmentation enthalpies for the loss of the consistent CH_3 group.

It should also be noted in passing that the homo-anomeric effect not only promotes fragmentation by injecting electron density into the antibonding orbital of the breaking S−R bond, it also sets up the necessary alignment of orbitals for the formation of the C=S bond in the thiocarbonyl product of fragmentation. As outlined previously, as the S−R bond assumes a more perpendicular orientation, the S−CH_3 bond assumes a more planar (and cis) arrangement with the future C=S bond, geometrically similar to the final thiocarbonyl product. Moreover, the alignment of the 2p(C•) orbital with the S−R bond can promote fragmentation since it facilitates the formation of the C=S π-bond. As a result, one would predict that the kinetics of fragmentation should also be favored by this homo-anomeric effect; thus, the R-groups bearing electron withdrawing substituents such as CN should fragment faster than would otherwise be predicted on the basis of steric and radical stabilization considerations.

The seemingly anomalous effects of methyl substitution in the $CH_3SC^•(CH_3)S{-}CXY(Ph)$ series can also be rationalized in terms of the relative strengths of the breaking S−R bonds. When additional (electron-donating) methyl substituents are included in the R-group, these counteract the energy lowering effect of the electron-withdrawing X-substituents on the pseudo-π^*-orbital of the S−R bond. Therefore, the electron accepting ability of this orbital is reduced, and the homo-anomeric effect weakens. At the same time, the electron donating ability of the adjacent sulfur atom is increased, and it is able to contribute more significantly to the stabilization of the unpaired electron. As a result of these factors, together with the increased steric interactions, the radical twists, adopting a geometry again approaching that of $CH_3SC^•(CH_3)SCH_3$. Because less electron density is promoted into the (antibonding) pseudo-π^*-orbital of the S−R bond, this bond is unexpectedly strengthened despite the increasing steric bulk of the R-group. This effect is seen most clearly in the $CH_3SC^•(CH_3)SCXYPh$ series of radicals. In the benzyl-substituted radical (i.e., X = Y = H), the S−R bond and the plane of the phenyl ring is almost perpendicular to the SCXYPh bond and parallel to the SC•S plane. In this conformation, electron density from the pseudo-π^*-orbital of the bond can be delocalized onto the aromatic ring, and the homo-anomeric effect is enhanced. However, with the inclusion of the additional methyl substituents at X and Y, the CXYPh group twists, and the $S_1{-}C_2{-}C_3{-}C_4$ dihedrals (see Figure 8) increase from 99° (X = Y = H), to 108° (X = H, Y = CH_3) and 123° (X = Y = CH_3). Because less electron density is accepted into the antibonding orbital of the S−CXYPh bond, it strengthens, and this counters the steric destabilization of the RAFT-adduct radical. As a result, the fragmentation enthalpies marginally increase from CH_2Ph to $C(CH_3)_2Ph$. Similar arguments can also be used to rationalize the relatively small decrease (by 6 kJ mol^{-1}) in fragmentation enthalpy from CH_2CN to $C(CH_3)_2CN$, despite the 27 kJ mol^{-1} increase in the stability of the



Z = CH_3

$X = Y = H$ $S_1C_2C_3C_4 = 99°$

$X = CH_3, Y = H$ $S_1C_2C_3C_4 = 108°$

$X = Y = CH_3$ $S_1C_2C_3C_4 = 123°$

Z = Ph

$X = Y = H$ $S_1C_2C_3C_4 = 97°$

$X = CH_3, Y = H$ $S_1C_2C_3C_4 = 101°$

$X = Y = CH_3$ $S_1C_2C_3C_4 = 122°$

Figure 8. Dihedral angles in selected RAFT-adduct radicals.

leaving group radical. The additional methyl substituents reduce the interaction of the pseudo-π^*-orbital with 2p($C^\bullet$). As a result of this weakened homo-anomeric interaction, less electron density is promoted into the pseudo-π^*-orbital of the S−R bond, its antibonding character is reduced, and the S−R bond strengthens. This strengthening of the S−R bond helps to counter the increased stability of the leaving radical, and as a result, the decrease in fragmentation enthalpy is only marginal.

Another factor affecting the fragmentation enthalpies for some of the systems is the potential for hydrogen bonding interactions. In the RAFT-adduct radicals bearing carbonyl substituents (i.e., R = CH_2COOCH_3, $CH(CH_3)COOCH_3$, and CH_2OCOCH_3), the carbonyl oxygen can undergo hydrogen bonding with hydrogens on the CH_3 Z-group of the RAFT-adduct radical. These interactions are of course disrupted by the fragmentation of the R group, and this contributes an enthalpy raising influence that depends on the strength of the disrupted H-bond. In the present systems, the H-bonding appears to be strongest for the radical bearing the model vinyl acetate leaving group (R = CH_2OCOCH_3, **23**), as is evident in the short O···H bond length (2.601 Å), and this contributes to the high fragmentation enthalpy for this system. The H-bonding is weaker in the radicals bearing methyl acrylate-type leaving groups (R = CH_2COOCH_3, **21**, and $CH(CH_3)COOCH_3$, **22**), the O···H bond lengths being 3.325 and 2.924 Å, respectively. This, together with the greater stability of the leaving group radicals, contributes to the lower fragmentation enthalpies in these cases. Within this series, the strongest bond occurs for the bulkier methyl substituted system (**22**), the close proximity of the carbonyl oxygen and CH_3 Z-group probably being enforced by steric factors. This stronger H-bonding interaction contributes an enthalpy raising influence, and as a result, the enthalpy decreases only marginally on methyl substitution of the R-group, despite the large increase in the stability of the leaving $R^\bullet$ radical.

In summary, the effects of the R-group on the fragmentation reaction consist of a complicated interplay of steric and electronic effects. Although the study generally confirmed the earlier suggestions that fragmentation is favored by R-groups that are either bulky and/or stable as radicals, other subtle yet important effects were also identified. In particular, it was seen that the R-group is able to modify the ability of the neighboring sulfur atom to stabilize the radical center. This in turn may lead to a compensating interaction between the lone pair of the second sulfur substituent (i.e., SCH_3) and the unpaired electron. This results in a conformational change in the radical and facilitates a homo-anomeric interaction between the unpaired electron and antibonding orbital of the S−R bond. The net result is that, although the inherent stability of the RAFT-adduct radical is not significantly affected, one of the breaking S−R bonds is weakened at the expense of the other. It was also seen that, through inducing conformational changes in the radical, bulky R-groups could interfere with these orbital interactions, and this often resulted in an unexpected strengthening of the breaking bond and thus an increase in the enthalpy of fragmentation. It was also seen that bulky and electronegative R-groups do affect the stability of the RAFT agent; hence, these effects have to be taken into account in quantitative computational studies of RAFT polymerization.

Effect of R and Z Acting in Combination. Having examined the isolated effects of the R- and Z-substituents, we are now in a position to examine the unusual synergistic effects that occur when various combinations of R- and Z-substituents are used. As a preface to this study, we first note that, owing to the large size of the systems, the fragmentation enthalpies and RSEs provided in Table 4 are reported at the (lower) RMP2/6-311+G(3df,2p) level of theory. In the assessment study presented previously, it was found that this level of theory should be reasonably reliable, provided that the leaving group radical does not bear a phenyl substituent. Moreover, the errors at this level of theory seem to be largely associated with the R-group; hence, this method should provide excellent relative values of the fragmentation enthalpies in comparisons in which the R-group is held constant and the Z-group is varied. In contrast, comparisons in which the R-group is varied while the Z-group is held constant may be less reliable at this level of theory. Hence, in the present work, we restrict these latter types of comparisons to situations (such as the series R = CH_2Ph, $CH(CH_3)Ph$, and $C(CH_3)_2Ph$ series) in which the set of leaving group radicals are closely related to one another.

Among reaction enthalpies provided in Tables 1, 2, and 4 are the enthalpies for the reactions $CH_3SC^\bullet(Z)SR \rightarrow CH_3SC(Z){=}S + {}^\bullet R$, with all possible combinations of Z = CH_3, Ph, and CH_2Ph and R = CH_3, CH_2Ph, CH_2COOCH_3, and $C(CH_3)_2CN$. On the basis of these values, we can calculate that changing the Z-substituent from CH_3 to Ph leads to an increase in fragmentation enthalpy by 28.8 (R = CH_3), 30.6 (R = CH_2Ph), 22.8 (R = CH_2COOCH_3), or 30.0 (R = $C(CH_3)_2CN$) kJ mol^{-1}. From these values, it will be seen that this Z-substituent effect is relatively independent of the R-group, even when the bulky $C(CH_3)_2CN$ substituent is considered. However, the one exception to this is the R = CH_2COOCH_3 system, for which the phenyl substituent effect is smaller by 6−8 kJ mol^{-1}. As noted previously, in the Z = CH_3 system, H-bonding (between hydrogens on the CH_3 Z-group and the carbonyl oxygen) may be playing a role, with the loss of H-bonding upon fragmentation contributing to an increased enthalpy. Of course, in the Z = phenyl system, these hydrogens are no longer available for hydrogen bonding, and this enthalpy raising influence is removed. This loss of H-bonding between the Z = CH_3 and Z = phenyl systems counters some of the enthalpy increase arising from the greater stabilization of the RAFT-adduct radical. In support of this notion, we note that the CH_2COOCH_3 substituent exerts a similar synergistic effect in the Z = benzyl systems. For these systems, changing the CH_3 Z-group to a benzyl increases the fragmentation enthalpy by 7.1 (R = CH_3), 4.0 (R = CH_2Ph), or 5.9 (R = $C(CH_3)_2CN$)

kJ mol^{-1} for the other R-groups but has no effect in the R = CH_2COOCH_3 system. As seen in Figure 4, the presence of the bulky benzyl group in the Z-position of the $CH_3SC^{\bullet}(CH_2Ph)SCH_2COOCH_3$ radical (**41**) forces the carbonyl group to angle away from the Z-group, preventing the H-bonding interaction. Whereas the loss of H-bonding on fragmentation contributes an enthalpy raising influence in the Z = CH_3 system, this influence is absent in the Z = benzyl system, and the enthalpy increase on changing Z = CH_3 to Z = benzyl is thus diminished (as compared to radicals bearing non-H-bonding R-groups).

H-bonding also plays a role in the systems bearing the model vinyl acetate leaving groups (i.e., R = CH_2OCOCH_3); however, in these systems the synergistic effects are more complicated. We first note that within the Z = OMe, OEt, O*i*Pr, and O*t*Bu series, the effect of the Z-group on the reaction enthalpy is relatively independent of whether the R-group is a CH_3 substituent or a CH_2OCOCH_3 substituent. However, the effect of changing the Z-group from a CH_3 substituent to a OCH_3 group does vary according to the R-group; the enthalpy decreasing by 38.8 kJ mol^{-1} when R = CH_3 but by 46.6 kJ mol^{-1} when R = CH_2OCOCH_3. Put another way, changing the R-group from CH_3 to CH_2OCOCH_3 increases the fragmentation enthalpy by 14.7 kJ mol^{-1} when Z = CH_3 but only by 6.9 kJ mol^{-1} when Z = OCH_3. What is intriguing about these results is that while H-bonding is lost upon fragmentation of the CH_2OCOCH_3 group from both $CH_3SC^{\bullet}(CH_3)SCH_2OCOCH_3$ and $CH_3SC^{\bullet}(OCH_3)SCH_2OCOCH_3$, the loss of H-bonding should have been more (rather than less) important in the Z = OCH_3 system. This is because in this radical there are two hydrogen bonds between the R- and the Z-group in the Z = OCH_3 system: the bond between the carbonyl oxygen and a hydrogen on the methoxy Z-group (2.428 Å) and a second bond between the methoxy oxygen and a hydrogen on the CH_2 fragment of the CH_2OCOCH_3 R-group (2.498 Å). This second bond is of course absent in the Z = CH_3 system. Moreover, the hydrogens on the CH_3 Z-group would be expected to be less acidic than their methoxy counterparts; thus, their H-bonding interaction is likely to be weaker. (Indeed, the H-bonding distance in this system is longer, being 2.601 Å.)

The synergistic effect of the Z- and R-groups on the fragmentation enthalpies in the xanthate-related systems appears instead to arise in the radical stabilities. At the RMP2/6-311+G(3df,2p) level of theory, the RSEs for the R = CH_3 systems are 57.0 (Z = CH_3) and 55.3 (Z = OCH_3) kJ mol^{-1}, while in the R = CH_2OCOCH_3 systems, they are 61.4 (Z = CH_3) and 47.4 (Z = OCH_3) kJ mol^{-1}. In other words, in the presence of a methyl R-group, changing the Z-group from methyl to methoxy has a minimal effect on radical stability, but in the presence of the CH_2OCOCH_3 R-group, the same change decreases the radical stability by 14 kJ mol^{-1}. This decline in radical stability outweighs the additional H-bonding interactions, thereby enabling the radical to fragment more easily. Although this explains the fragmentation enthalpies, these substituent effects on radical stability are somewhat counterintuitive. As discussed previously, the radical stabilizing properties of the CH_3 and OCH_3 substituents in isolation are markedly different, the electron donating OCH_3 group providing greater stabilization than the CH_3 group. However, in the RAFT-adduct radicals of the form $CH_3SC^{\bullet}(Z)SCH_3$, the stabilizing effect of electron donation is diminished by the presence of the two S−R substituents; hence, the RSEs for the Z = CH_3 and Z = OCH_3 radicals are very similar. Likewise, in isolation, the R-group is capable of modifying the ability of the SR-group to stabilize the unpaired electron. However, in the RAFT-adduct radicals of the form $CH_3SC^{\bullet}(CH_3)SR$, this does not affect the radical stability because the stabilization from the other CH_3S substituent can increase or decrease in compensation. It is therefore remarkable that, although neither of the OCH_3 Z-substituent or the CH_2OCOCH_3 R-substituent significantly affects the stability of the RAFT-adduct radical in isolation, in the combination they significantly destabilize the radical. Moreover, the effect is unlikely to be the result of simple steric crowding, as this should have been more significant in the reference closed-shell species (and hence the RSE would then have increased rather than decreased). The decline in radical stability may be related to the increased σ withdrawal (acting on the electron deficient radical center) when both the OCH_3 Z-substituent and the CH_2OCOCH_3 R-substituent is present. In this regard, we note that the total charge on the radical center (which of course is the sum of the σ and π-charges) is slightly less negative in the $CH_3SC^{\bullet}(OCH_3)SCH_2OCOCH_3$ radical (−0.084) as compared to the $CH_3SC^{\bullet}(OCH_3)SCH_3$ radical (−0.105). Normally, these σ-withdrawing substituents stabilize a radical because the σ withdrawal is counteracted by increased lone pair donation but, as seen in the present work, the effects of lone pair donation diminish in the presence of the other lone pair donor substituents; hence, σ withdrawal becomes more important.

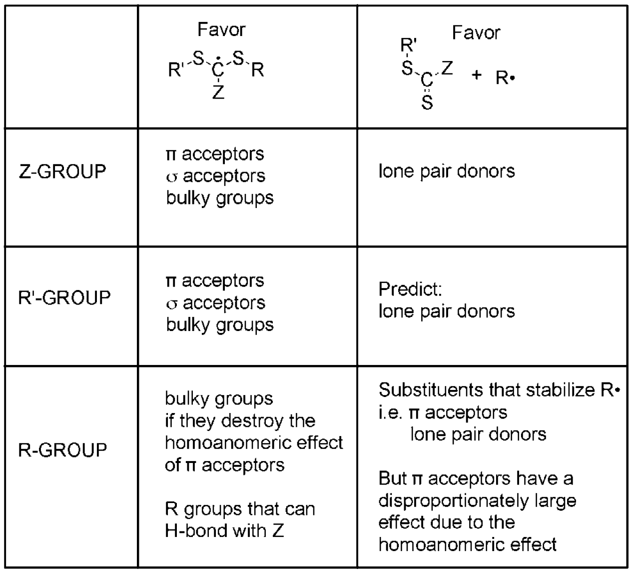
Another unusual synergistic effect is seen in the R = CH_2Ph, $CH(CH_3)Ph$, and $C(CH_3)_2Ph$ series. When Z = CH_3, the fragmentation enthalpies (for loss of the $R^{\bullet}$ radical) are relatively constant as the R-group is varied. As noted previously, this is the result of competing factors. On one hand, the increasing stability of the leaving $R^{\bullet}$ radical contributes an enthalpy lowering influence. On the other hand, the increasing methyl substitution of the R-group reduces the electron withdrawing effect of the phenyl and distorts the radical geometry in such a manner that the S−R bond becomes less aligned with the 2p($C^{\bullet}$), and the plane of the phenyl ring in the leaving CXYPh group becomes less perpendicular to the S−R bond. As a result, the homo-anomeric interaction between the pseudo-π^*-orbital of the breaking S−CXYPh bond and unpaired electron diminishes. Since less electron density is promoted into the antibonding orbital of this bond, it is strengthened. In the Z = Ph systems, these competing factors should also apply, and in this regard, we note that the $S_1C_2C_3C_4$ dihedrals are very similar between corresponding Z = CH_3 and Z = phenyl systems (see Figure 8). However, unlike the Z = CH_3 systems, in the Z = phenyl systems, the R-group has a somewhat unusual effect, with the change from R = CH_2Ph to R = $CH(CH_3)Ph$ significantly increasing the fragmentation enthalpy (by 10.9 kJ mol^{-1}) but decreasing the radical stability (by 9 kJ mol^{-1}). In contrast, changing from R = CH_2Ph to R = $C(CH_3)_2Ph$ increases the radical stability (by 6.8 kJ mol^{-1}) and fragmentation enthalpy (by 3.1 kJ mol^{-1}) only marginally (in a manner similar to the Z = CH_3 systems).

Thus, in the presence of the phenyl Z-substituent, the 1-phenylethyl group both destabilizes the radical and increases the fragmentation enthalpy. This unusual behavior arises in a sterically induced conformational change in the RAFT-adduct radical. In the R = benzyl system, the radical center is virtually planar (the pyramidalization angle is 1.2°), allowing the unpaired electron to delocalize onto the aromatic ring of the Z-group. However, when R = 1-phenylethyl, steric interactions cause the radical center to pyramidalize slightly (the angle becomes 8.8°), reducing the radical stabilization associated with the phenyl Z-group. As a result, the RSE decreases. When the extra methyl group is added (i.e., R = cumyl), the geometry is pyramidalized in both directions, and as a result, the planarity of the radical center is restored (the angle is 1.6°), and the stability of the radical increases again. By lowering the energy of 2p(C$^•$), this pyramidalization of the radical center would be expected to diminish the homo-anomeric effect more significantly in the R = 1-phenylethyl system, as compared to the R = benzyl and R =cumyl systems. As the homo-anomeric effect is diminished, less electron density is promoted into the antibonding orbital of the S−R bond. As a result, although the radical is destabilized as a whole, the S−R bond is again unexpectedly strengthened, resulting in an increase (rather than the expected decrease) in the fragmentation enthalpy.

It should be stressed that, in general, the Z- and R-substituent effects are relatively independent of one another. However, there are some important exceptions. In particular, the presence of bulky R- and Z-groups can lead to sterically induced conformational changes in the radical, which can in turn affect its stability and also the strength of the breaking S−R bond. In addition, when the R-substituent contains a carbonyl group (as in model methyl acrylate or vinyl acetate leaving groups), intramolecular H-bonding interactions may occur, and these will depend on the nature of the Z-group. It was also seen that combinations of lone-pair donor/σ-withdrawing substituents can (marginally) destabilize the RAFT-adduct radical, as the stabilizing effect from the lone pair donation becomes increasingly less important as the σ destabilization becomes more important. This effect may be contributing to the effectiveness of xanthates in controlling vinyl acetate polymerization.

4. Conclusions

In the present work, we have reported the radical stabilization energies for a wide variety of model RAFT-adduct radicals ($CH_3SC^•ZSR$) and analyzed these effects on radical stability in terms of simple molecular orbital and steric considerations. The results have been combined with the corresponding enthalpies of fragmentation (i.e., $CH_3SC^•ZSR \rightarrow CH_3SC(Z){=}S + {}^•R$ and $CH_3SC^•ZSR \rightarrow {}^•CH_3 + S{=}C(Z)SR$), to interpret the dramatic effects of substituents on addition−fragmentation in the RAFT process. Although the substituent effects are the result of a complicated array of factors, they can be relatively easily understood in terms of the key orbital interactions between the donor SR-groups and the Z-group and the impact of these interactions on the geometry of the radical and the strength of the breaking S−R bonds. Steric effects can play a major role in disrupting these interactions, which can in turn have some unexpected consequences. Some of the main findings of the study are as follows. (A simplified summary is also provided in Figure 9.)



	Favor	Favor
Z-GROUP	π acceptors σ acceptors bulky groups	lone pair donors
R'-GROUP	π acceptors σ acceptors bulky groups	Predict: lone pair donors
R-GROUP	bulky groups if they destroy the homoanomeric effect of π acceptors R groups that can H-bond with Z	Substituents that stabilize R• i.e. π acceptors lone pair donors But π acceptors have a disproportionately large effect due to the homoanomeric effect

Figure 9. Principal substituent effects on the addition−fragmentation equilibrium.

The stability of the RAFT-adduct radical ($CH_3SC^•(Z)SR$) is dominated by lone pair donation from the two sulfur substituents. These substituents strongly stabilize the radical, and as a result, it appears to be difficult to design unstable RAFT-adduct radicals. The sulfur substituents also minimize the electronic effect of the R-group on radical stability, and the stabilizing effect of the lone pair donor Z-groups (such as Cl, OCH_3, and NH_2). However, the stability of the RAFT-adduct radical can be further enhanced by unsaturated π-accepting Z-substituents (such as phenyl, naphthyl, and CN), and RAFT-adduct radicals bearing such substituents are predicted to be relatively long-lived species. The steric properties of the Z- and R-substituents can also have an effect on the stability of the RAFT-adduct radical, with the bulkier substituents inducing conformational changes that interfere with the stabilizing effects of the SCH_3 substituents.

The stability of the RAFT agent (S=C(Z)SR) is strongly enhanced by lone pair donation from the Z-group (as in the xanthates and dithiocarbamates) and strongly diminished by σ withdrawal (as in the RAFT agents bearing Z-substituents such as CN or CF_3). Electron-withdrawing R-groups such as CH_2CN can also destabilize the RAFT agent by reducing the electron donation from the SR group. The steric effects of the R- and Z-groups are more pronounced in the RAFT agent, as compared with the corresponding RAFT-adduct radical. As a result, bulky groups tend to destabilize the RAFT agent, relative to the RAFT-adduct radical, and thus increase the fragmentation enthalpy.

Although the fragmentation enthalpies are largely governed by the (radical) stabilities of the RAFT-adduct radical and leaving group radicals and the stabilities of the product RAFT agents, the strength of the breaking S−R bond is also an important factor. It was found that, although the R-group did not significantly affect the overall stability of the RAFT-adduct radical, it did affect the relative strengths of the CH_3−S and S−R bonds. In essence, when the R-group modifies the donation ability of the sulfur substituent, the SCH_3 increases or decreases the strength of its stabilizing interaction with the unpaired electron in compensation. This results in a conformational change in the radical, which (for the substituents considered in the present work) renders the R-group a more effective leaving group and the CH$_3$ group a less effective leaving group. An unexpected consequence of these interactions is that bulky R-groups, which can cause conformational changes that interfere with these orbital interactions, can sometimes strengthen the breaking S–R bond, despite destabilizing the radical as a whole.

From a practical point of view, this study suggests that significantly destabilizing the RAFT-adduct radical (as compared with Z = CH$_3$) may be difficult without moving to non-RAFT systems, such as S=P analogues. However, where necessary, π-accepting substituents such as phenyl, naphthyl, or CN can be used to stabilize the RAFT-adduct radical. The use of lone pair donor substituents, which have already been exploited in the form of xanthates and dithiocarbamates for vinyl acetate polymerization, stabilize the S=C bond and thus help to increase the fragmentation of poor leaving groups. At the other extreme, for relatively stable propagating radicals, the C=S bond of the RAFT agent can be destabilized using σ-withdrawing Z-substituents, such as CN and CF$_3$, with the latter substituent predicted to provide an excellent, nonretarding RAFT agent for such cases.

Acknowledgment. We gratefully acknowledge generous allocations of computing time on the Compaq Alphaserver of the National Facility of the Australian Partnership for Advanced Computing and the Australian National University Supercomputing Facility, useful discussions with Profs. Leo Radom and Chris Easton, and provision of an Australian Research Council postdoctoral fellowship (M.L.C.).

Supporting Information Available: Tables S1–S4 showing the B3-LYP/6-31G(d) optimized geometries (in the form of GAUSSIAN archive entries) for the radicals, alkanes, and thiocarbonyl compounds used in the calculation of the radical stabilization energies and β-scission enthalpies in Tables 1–4, respectively. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Chiefari, J.; Chong, Y. K. B.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P. T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1998**, *31*, 5559–5562.

(2) Hawker, C. J.; Bosman, A. W.; Harth, E. *Chem. Rev.* **2001**, *101*, 3661–3688.

(3) Wang, J. S.; Matyjaszewski, K. *J. Am. Chem. Soc.* **1995**, *117*, 5614–5615.

(4) Le, T. P. T.; Moad, G.; Rizzardo, E.; Thang, S. H. PCT Int. Appl. WO 9801478 A1 980115 1998; *Chem. Abstr.* **1998** *128*, 115390.

(5) Krstina, J.; Moad, G.; Rizzardo, E.; Winzor, C. L.; Berge, C. T.; Fryd, M. *Macromolecules* **1995**, *28*, 5381.

(6) Delduc, P.; Tailhan, C.; Zard, S. Z. *J. Chem. Soc., Chem. Commun.* **1988**, 308–310.

(7) Charmot, D.; Corpart, P.; Michelet, D. Zard, S. Z., Biadatti, T. PCT Int. Appl. WO 9858974, 1998; *Chem Abstr.* **1999**, *130*, 82018

(8) Charmot, D.; Corpart, P.; Michelet, D.; Zard, S. Z.; Biadatti, T. *Macromol. Symp.* **2000**, *150*, 23.

(9) See, for example, the radical stabilization energies reported in Table 3.

(10) Lowe, A. B.; McCormick, C. L. *Aust. J. Chem.* **2002**, *55*, 367–379.

(11) Tsuji, Y.; Ejaz, M.; Sato, K.; Goto, A.; Fukuda, T. *Macromolecules* **2001**, *34*, 8872–8878.

(12) Ferguson, C. J.; Hughes, R. J.; Pham, B. T. T.; Hawkett, B. S.; Gilbert, R. G.; Serelis, A. K.; Such, C. H. *Macromolecules* **2002**, *35*, 9243–9245.

(13) Barner-Kowollik, C.; Dalton, H.; Davis, T. P.; Stenzel, M. H. *Angew. Chem., Int. Ed.* **2003**, *42*, 3664–3668.

(14) Sumerlin, B. S.; Lowe, A. B.; Thomas, D. B.; McCormick, C. L. *Macromolecules* **2003**, *36*, 5982–5987.

(15) Chen, M.; Ghiggino, K. P.; Launikonis, A.; Mau, A. W. H.; Rizzardo, E.; Saase, W. H. F.; Thang, S. H.; Wilson, G. J. *J. Mater. Chem.* **2003**, *13*, 2696–2700.

(16) Henry, D. J.; Coote, M. L.; Gómez-Balderas, R.; Radom, L. *J. Am. Chem. Soc.* **2004**, *126*, 1732–1740.

(17) Coote, M. L. *Macromolecules* **2004**, *37*, 5023–5031.

(18) Coote, M. L.; Radom, L. *Macromolecules* **2004**, *37*, 590–596.

(19) Coote, M. L.; Radom, L. *J. Am. Chem. Soc.* **2003**, *125*, 1490–1491.

(20) Feldermann, A.; Coote, M. L.; Stenzel, M. H.; Davis, T. P.; Barner-Kowollik, C. *J. Am. Chem. Soc.* **2004**, *126*, 15915–15923.

(21) Farmer, S. C.; Patten, T. E. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *A40*, 555–563.

(22) Chiefari, J.; Mayadunne, R. T. A.; Moad, C. L.; Moad, G.; Rizzardo, E.; Postma, A.; Skidmore, M. A.; Thang, S. H. *Macromolecules* **2003**, *36*, 2273–2283.

(23) Chong, Y. K.; Krstina, J.; Le, T. P. T.; Moad, G.; Postma, A.; Rizzardo, E.; Thang, S. H. *Macromolecules* **2003**, *36*, 2256–2272.

(24) Adamy, M.; van Herk, A. M.; Destarac, M.; Monteiro, M. J. *Macromolecules* **2003**, *36*, 2293–2301.

(25) Destarac, M.; Taton, D.; Zard, S. Z.; Saleh, T.; Six, I. *ACS Symp. Ser.* **2003**, *854*, 536–550.

(26) Destarac, M.; Bzducha, W.; Taton, D.; Gauthier-Gillaizeau, I.; Zard, S. Z. *Macromol. Rapid Commun.* **2002**, *23*, 1049–1054.

(27) Stenzel, M. H.; Cummins, L.; Roberts, G. E.; Davis, T. P.; Vana, P.; Barner-Kowollik, C. *Macromol. Chem. Phys.* **2003**, *204*, 1160–1168.

(28) Moad, G.; Chiefari, J.; Chong, Y. K.; Krstina, J.; Mayadunne, R. T. A.; Postma, A.; Rizzardo, E.; Thang, S. H. *Polym. Int.* **2000**, *49*, 993–1001.

(29) The RSEs (kJ mol^{-1}) for the X-CH$_2$SCH$_2^{\bullet}$ radicals at the G3(MP2)-RAD level of theory are 32.9 (X = CN) and 40.7 (X = H). The latter value is taken directly from ref 19.

(30) This is given by the formula $k_{\mathrm{tr}} = k_{\mathrm{add}}(k_\beta/(k_\beta + k_{-\mathrm{add}}))$, where k_{add}, $k_{-\mathrm{add}}$, and k_β are as defined in Scheme 1. It should be noted that this formula is only correct if the quasi-steady-state assumption holds, if the adduct does not undergo side reactions, and if the fragmentation step is irreversible. In real systems, and particularly in retarded polymerizations, the relationship between the observed transfer coefficient and the individual rate coefficients will be more complex.

(31) Barner-Kowollik, C.; Quinn, J. F.; Uyen Nguyen, T. L.; Heuts, J. P. A.; Davis, T. P. *Macromolecules* **2001**, *34*, 7849–7857.

(32) Moad, G.; Chiefari, J.; Mayadunne, R. T. A.; Moad, C. L.; Postma, A.; Rizzardo, E.; Thang, S. H. *Macromol. Symp.* **2002**, *182*, 65–80.

(33) Rizzardo, E.; Chiefari, J.; Mayadunne, R. T. A.; Moad, G.; Thang, S. H. *ACS Symp. Ser.* **2000**, *786*, 278–296.

(34) Destarac, M.; Charmot, D.; Franck, X.; Zard, S. Z. *Macromol. Rapid Commun.* **2000**, *21*, 1035–1039.

(35) Mayadunne, R. T. A.; Rizzardo, E.; Chiefari, J.; Chong, Y. K.; Moad, G.; Thang, S. H. *Macromolecules* **1999**, *32*, 6977–6980.

(36) Perrier, S.; Barner-Kowollik, C.; Quinn, J. F.; Vana, P.; Davis, T. P. *Macromolecules* **2002**, *35*, 8300–8306.

(37) Henry, D. J.; Parkinson, C. J.; Mayer, P. M.; Radom, L. *J. Phys. Chem. A* **2001**, *105*, 6750–6756.

(38) See, for example: Fischer, H.; Radom, L. *Angew. Chem., Int. Ed. Engl.* **2001**, *40*, 1340–1371, and references therein.

(39) Zavitsas, A. A. *J. Chem. Educ.* **2001**, *78*, 417–419.

(40) Matsunaga, N.; Rogers, D. W.; Zavitsas, A. A. *J. Org. Chem.* **2003**, *68*, 3158–3172.

(41) Coote, M. L.; Pross, A.; Radom, L. *Org. Lett.* **2003**, *5*, 4689–4692.

(42) Coote, M. L.; Pross, A.; Radom, L. In *Fundamental World of Quantum Chemistry: A Tribute to the Memory of Per-Olov Löwdin, Volume III*; Brändas, E. J., Kryachko, E. J., Eds.; Kluwer-Springer: New York, 2004; p 581–595.

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

(44) Koch, W.; Holthausen, M. C. *A Chemist's Guide to Density Functional Theory*; Wiley-VCH: Weinheim, 2000.

(45) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.;

Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; 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.; Andres, J. L.; Gonzalez, C.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *GAUSSIAN 98*; Gaussian, Inc.: Pittsburgh, PA, 1998

(46) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery Jr., J. A.; 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.; 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 B.03*; Gaussian, Inc.: Pittsburgh, PA, 2003.

(47) Werner, H.-J.; Knowles, P. J.; Amos, R. D.; Bernhardsson, A.; Berning, A.; Celani, P.; Cooper, D. L.; Deegan, M. J. O.; Dobbyn, A. J.; Eckert, F.; Hampel, C.; Hetzer, G.; Korona, T.; Lindh, R.; Lloyd, A. W.; McNicholas, S. J.; Manby, F. R.; Meyer, W.; Mura, M. E.; Nicklass, A.; Palmieri, P.; Pitzer, R.; Rauhut, G.; Schütz, M.; Stoll, H.; Stone, A. J.; Tarroni, R.; Thorsteinsson, T. *MOLPRO 2000.6*; University of Birmingham: Birmingham, 1999.

(48) Henry, D. J.; Sullivan, M. B.; Radom, L. *J. Chem. Phys.* **2003**, *118*, 4849−4860.

(49) Coote, M. L.; Wood, G. P. F.; Radom, L. *J. Phys. Chem. A* **2002**, *106*, 12124−12138.

(50) Gómez-Balderas, R.; Coote, M. L.; Henry, D. J.; Radom, L. *J. Phys. Chem. A* **2004**, *108*, 2874−2883.

(51) Coote, M. L. *J. Phys. Chem. A* **2004**, *108*, 3865−3872.

(52) Vreven, T.; Morokuma, K. *Theor. Chem. Acc.* **2003**, *109*, 125−132.

(53) Bernardi, F.; Epiotis, N. D.; Cherry, W.; Schlegel, H. B.; Whangbo, M.-H.; Wolfe, S. *J. Am. Chem. Soc.* **1976**, *98*, 469−478.

(54) NBO charges calculated at the B3-LYP/6-311+G(3df,2p)//B3-LYP/6-31G(d) level of theory.

(55) Coote, M. L. *J. Phys. Chem. A* **2005**, in press.

(56) See, for example: (a) Dobbs, A. J.; Gilbert, B. C.; Norman, R. O. C. *J. Chem. Soc. A* **1971**, 124. (b) Dobbs, A. J.; Gilbert, B. C.; Norman, R. O. C. *J. Chem. Soc., Perkin Trans 2* **1972**, 786. (c) Griller, D.; Nonhebel, D. C.; Walton, J. C. *J. Chem. Soc., Perkin Trans. 2* **1984**, 1817. (d) Beckwith, A. L. J., Brumby, S. *J. Chem. Soc., Perkin Trans 2* **1987**, 1801. (e) Henry, D. J.; Beckwith, A. L. J.; Radom, L. *Aust. J. Chem.* **2003**, *56*, 429−436.

(57) Note that this value is the ratio of the k_{add} and k_{frag} rate coefficients reported in this previous work. The equilibrium constant quoted in this previous paper (13.2 L mol^{-1}) is incorrect, having been mistakenly calculated as the inverse ratio: $k_{\mathrm{frag}}/k_{\mathrm{add}}$.

MA047814A