Macromolecules **2004,** *37,* 5023−5031 **5023**

Ab Initio Study of the Addition−Fragmentation Equilibrium in RAFT Polymerization: When Is Polymerization Retarded?

Michelle L. Coote*

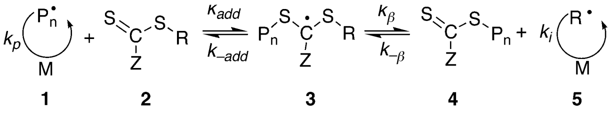
Research School of Chemistry, Australian National University, Canberra, ACT 0200, Australia

Received March 21, 2004; Revised Manuscript Received April 26, 2004

ABSTRACT: High level ab initio calculations of the addition−fragmentation equilibrium constants at 333 K were performed for model RAFT reactions: $R^{\bullet} + S{=}C(Z)SCH_3 \rightarrow R{-}SC^{\bullet}(Z)SCH_3$, for all combinations of Z = CH_3, phenyl, or benzyl with R = CH_3, benzyl, CH_2COOCH_3, or $C(CH_3)_2CN$. The results indicate that slow fragmentation of the polymeric RAFT-adduct radical is responsible for rate retardation in cumyl dithiobenzoate mediated polymerization of styrene and methyl acrylate. They also confirm that rate retardation should be relieved by changing the phenyl Z substituent to a benzyl group and that inhibition should be relieved by using a RAFT agent with a $C(CH_3)_2CN$ leaving group. The equilibrium constants are extremely sensitive to the nature of the R and Z substituents, with a 13 orders of magnitude variation over the 12 reactions considered. The effects of these substituents on the reaction enthalpy are generally consistent with the trends expected on the basis of radical stabilization arguments. However, there are additional steric effects on the reaction entropy, and certain synergistic effects between the R and Z substituents on the stability of the RAFT-adduct radicals, which complicate the trends in the equilibrium constants.

1. Introduction

In recent years, the field of free-radical polymerization has been revolutionalized by the development of techniques for controlling the molecular weight and architecture of the resulting polymer, including nitroxide-mediated polymerization (NMP),[1] atom transfer polymerization (ATRP),[2] and reversible addition fragmentation chain transfer (RAFT) polymerization.[3] The basic principle of these processes is to protect the majority of the growing polymer chains from bimolecular termination through their reversible trapping into some dormant form. In the case of RAFT polymerization, thiocarbonyl compounds (known as RAFT agents, **2**) reversibly react with the growing polymeric radical (**1**) via the chain transfer reaction shown in reaction 1, producing a polymeric thiocarbonyl compound (**4**) as the dormant species.[3]



(1)

To achieve control, a delicate balance of the forward and reverse rates of addition (k_{add} and $k_{-\mathrm{add}}$) and fragmentation (k_β and $k_{-\beta}$), together with the rates of reinitiation (k_{i}) and propagation (k_{p}), is required. It is therefore important to have a complete mechanistic understanding of the process and understand the role of substituent effects on each of the individual reactions.

Although it is generally accepted that the main elements of the RAFT mechanism are as described in eq 1 above, there has been considerable debate as to whether additional side-reactions can occur under certain circumstances. In particular, to explain the observed rate retardation in cumyl dithiobenzoate (CDB) mediated systems, a number of workers have postulated the existence of a cross-termination reaction, in which the RAFT-adduct radical terminates with itself or with the propagating radical. However, the experimental evidence for the kinetic significance of this reaction has been contradictory.

At the center of this controversy are alternative experimental measurements of the addition−fragmentation equilibrium constants ($K_{\mathrm{eq}} = k_{\mathrm{add}}/k_\beta$) for the CDB-mediated polymerization of styrene at 333 K. Experiments based on the combined analysis of data for the overall rate of polymerization and the total radical concentration (as obtained from ESR), obtain low values for the equilibrium constant, such as 55 L mol^{-1}.[4] These imply that the fragmentation reaction is relatively fast compared with the rate of addition and that the polymerization should not be retarded unless other reactions (such as termination) are occurring. By contrast, experimental measurements based on the combined analysis of data for the overall rate of polymerization and the molecular weight distribution of the polymer (as obtained from GPC), obtain high values for the equilibrium constant, such as 1.6×10^7 L mol^{-1}.[5] These values imply that the fragmentation step is relatively slow compared with the rate of addition, and this slow fragmentation is sufficient to explain the rate retardation without recourse to additional side-reactions.

The source of this 6 orders of magnitude discrepancy has already been the topic of some debate;[6−8] nonetheless, it is worth noting that this discrepancy arises (at least in part) in the inherent model-based assumptions used in the alternative experimental techniques. In the case of (a) the ESR data,[4] the estimation of the equilibrium constant rests upon the validity of the quasi-steady-state assumption (i.e., that the ratios of the concentrations of the propagating radical and the RAFT-adduct radical are constant).[8] However, a kinetic analysis of the RAFT mechanism has shown that this assumption only holds over normal conversions when the equilibrium constant is very low, that is, so low as to *not* cause rate retardation.[9] For higher equilibrium

---

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

10.1021/ma049444w CCC: $27.50

constants, it was shown that the steady state is not established until very late in the reaction, and recent experimental evidence[10] indicates that this is indeed the case for CDB-mediated polymerizations. In the case of (b) the molecular weight data,[5] the estimation of the equilibrium constant does not rest upon the quasi-steady-state assumption. However, by not making this assumption, it becomes difficult to use such data to measure *both* the rate coefficient for the termination side reaction and the equilibrium constant, independently of one another. To measure the equilibrium coefficients in the previous work, the authors assumed that the termination side reaction was not significant, and hence all rate retardation was attributed to slow fragmentation. As a result, the measured equilibrium constant was higher than in the ESR studies. In essence, the two alternative experimental procedures measure lower and upper bounds for the equilibrium constant, corresponding to the extremes of (a) *no* rate retardation being attributable to slow fragmentation or (b) *all* rate retardation being attributable to slow fragmentation.

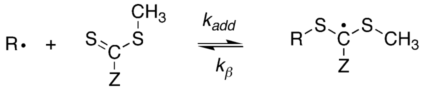
Given this problem, more direct strategies for establishing the causes of rate retardation in certain CDB-mediated systems have been explored. For example, Barner-Kowollik et al.[11] examined the stability of the RAFT adduct radical by initiating the CDB-mediated polymerizations at a low temperature (at which polymerization does not occur) and then holding the reactants dormant at this temperature for periods of up to 1 h. Upon heating, and without further initiation, normal RAFT polymerization was shown to occur, implying that the RAFT adduct radical (or some species reversibly derived from it) had remained intact during the dormant period. Although this suggests that the RAFT adduct radical is relatively stable at the lower temperature, this does not necessarily preclude the presence of termination side-reactions in RAFT polymerization. To establish the extent of termination, the products of CDB-mediated polymerizations have also been examined. However, the results of such studies have been inconclusive. For example, it has been demonstrated that the three-arm star, formed by coupling between the propagating radical and the RAFT-adduct, can be synthesized under special, non-RAFT conditions.[4,8,12] However, this in itself does not necessarily imply that such reactions could compete effectively with the other steps in the RAFT process under normal conditions. Indeed, a detailed electrospray ionization mass spectrometry study of the products of an actual RAFT polymerization failed to find these termination products in situ.[13] This was despite the fact that the study was sensitive enough to identify all of the expected termination products from the normal bimolecular termination reactions. Interestingly, the study identified peaks corresponding to the molecular weight of the RAFT-adduct radical itself, which would suggest that the radical is very stable and thus slow to fragment. However, within reasonable experimental uncertainty, the possibility that these peaks were due instead to a disproportionation reaction involving the adduct could not be ruled out. More recently, an NMR study has identified in situ the products of coupling reactions involving the RAFT adduct.[14] However, the authors of this study were careful to acknowledge that these products were observed at very low concentrations, and only when large concentrations of the RAFT agent were used.

To summarize, the balance of evidence suggests that the termination side reactions are certainly possible, but they appear to be significant only under extreme reaction conditions. The extent to which these reactions occur under normal RAFT conditions, and the extent to which they cause rate retardation, is yet to be established. More generally, current experimental techniques for measuring the addition−fragmentation equilibrium constants in RAFT polymerization rely upon kinetic model-based assumptions, and depending on the assumptions made, enormous discrepancies in the measured equilibrium constants can arise. This in turn makes it difficult to study the effects of substituents on the individual reactions.

Computational quantum chemistry can provide a means of addressing these problems by allowing for direct calculation of the equilibrium constants in RAFT polymerization. Provided a high level of theory is used, such calculations can achieve chemical accuracy and have the advantage that they do not rely upon the validity of kinetic model-based assumptions. Recently, this approach was used to calculate the addition−fragmentation equilibrium constants at 333 K for simple fragmentation reactions of the form, $^{\bullet}CH_3 + S{=}C(Z)SCH_3 \rightarrow CH_3SC^{\bullet}(Z)S{-}CH_3$, for Z = phenyl and benzyl.[15] The values obtained (5.4×10^9 L mol^{-1} and 7.6×10^6 L mol^{-1}, respectively) were very high and indicated that slow fragmentation alone could explain rate retardation in CDB-mediated systems. They were also consistent with the experimental observation that replacing a phenyl group with a benzyl group in the Z position significantly increases the fragmentation rate and could thus relieve rate retardation.

Despite these results, the magnitude of the fragmentation rate coefficient in RAFT polymerization remains a point of controversy.[6−8] The relevance of the calculations, which correspond to a model reaction in the gas phase, for RAFT polymerization has been questioned.[8] In particular, it has been noted that the fragmentation reaction is very sensitive to the nature of the leaving group, and the use of a methyl radical may not provide an adequate model of typical leaving groups in experimental systems. Indeed, the validity of this criticism has been highlighted by a more recent ab initio study[16] of model xanthate-mediated polymerizations of vinyl acetate (Z = O−Me, O−Et, O−*i*Pr, O−*t*Bu and R = CH_2OCOCH_3), which yielded equilibrium constants that differ by as much as 10 orders of magnitude from those for the Z = phenyl, R = CH_3 model system. It is therefore important to extend the earlier work to consider a range of more realistic leaving groups.

In the present work, high-level ab initio molecular orbital calculations have been used to calculate the addition−fragmentation equilibrium constants for a series of model RAFT reactions of the form



(2)

with all combinations of Z = CH_3, phenyl, and benzyl, and R = CH_3, benzyl, CH_2COOCH_3, and $C(CH_3)_2CN$. The substituents were chosen to model a range of known retarded and nonretarded RAFT polymerizations. In the Z position, the phenyl and benzyl Z substituents are present in retarding (e.g., cumyl dithiobenzoate, CDB) and nonretarding (e.g. cumyl phenyl dithioacetate[17,18])

RAFT agents, respectively. In the R position, the benzyl and CH_2COOCH_3 leaving groups are the simplest possible chemical models of the propagating radical in styrene and methyl acrylate polymerization, respectively. Both of these monomers are retarded (at 333 K) in the presence of CDB but not in the presence of cumyl phenyl dithioacetate. The $C(CH_3)_2CN$ leaving group was included in the study as this leaving group (when replacing the cumyl in CDB) is known to relieve the initial inhibition period in RAFT polymerization of methyl acrylate.[19] Finally, the methyl substituents in the R and Z positions are used as reference substituents.

The aims of the research are 2-fold. First, by examining the magnitude of the calculated equilibrium constants, it is hoped to establish whether these are sufficient to explain rate retardation. Second, by comparing the equilibrium constants for the different substituents (acting alone and in combination with one another), it is hoped to provide a deeper understanding of the effects of substituents in these reactions. The focus of the present study is the equilibrium constants for the addition−fragmentation reactions as these govern the extent to which rate retardation occurs. The individual rate coefficients for addition and fragmentation, which are important for the control of the polymerization, will be the subject of a separate study.

2. Computational Procedures

Standard ab initio molecular orbital theory[20] and density functional theory[21] calculations were carried out using Gaussian 98[22] and MOLPRO 2000.6[23] Unless noted otherwise, calculations on radicals were performed with an unrestricted wave function. In cases where a restricted-open-shell wave function has been used, it is designated with an "R" prefix.

Equilibrium coefficients at 333 K were calculated for the following addition−fragmentation reactions: $R^\bullet + S{=}C(Z)SCH_3 \rightarrow R{-}SC^\bullet(Z)SCH_3$, for Z = CH_3, phenyl, and benzyl and R = CH_3, benzyl, CH_2COOCH_3, and $C(CH_3)_2CN$. All combinations of R and Z substituents were considered; combinations in which *both* R and Z are *not* CH_3 are referred to as disubstituted systems, whereas the other combinations are referred to as monosubstituted systems. The equilibrium coefficient for the above reaction is given by eq 3

$$K_{eq} = V^\circ \exp(-\Delta G/RT) \tag{3}$$

where V° is the basis volume (1 mol of ideal gas at 333 K, V° = 27.337 L mol^{-1}) used in calculating the translational contribution to the entropy and ΔG is the Gibb's free energy of reaction and is given by the standard formula, $\Delta G = \Delta H - T\Delta S$. The total entropy of the reaction (ΔS) at 333 K was obtained by summing the electronic, vibrational, translational, external rotational, and (where relevant) internal rotational contributions. The total enthalpy of reaction (ΔH) at 333 K was obtained by adding the temperature correction and the zero-point vibrational energy to the energy change of the reaction. The "temperature correction" was calculated as the sum of the vibrational, translational, external rotational, and (where relevant) internal rotational contributions to the enthalpy of the reaction at a specific temperature. These various quantities were obtained as follows.

The geometries of the reactants and products were optimized at the B3-LYP/6-31G(d) level of theory. For each species considered, care was taken to ensure that the optimized structure was the global (rather than merely local) minimum energy structure by first performing extensive conformational searches at the HF/6-31G(d) level. Having obtained the optimized B3-LYP/6-31G(d) geometries, improved energies were then calculated at the G3(MP2)-RAD[24] level of theory (for the monosubstituted systems) and the RMP2/6-311+G(3df,2p) level of theory (for the larger disubstituted systems). These energies were then used to calculate the total energy change for the reaction. It has previously been shown that G3(MP2)-RAD provides accurate absolute reaction enthalpies and RMP2/6-311+G(3df,2p) provides reasonable absolute values and excellent relative values, for radical addition to C═S double bonds.[25]

Using the B3-LYP/6-31G(d) optimized geometries, frequency calculations were then performed at the B3-LYP/6-31G(d) level of theory, and the scaled[26] frequencies were used to calculate the zero-point vibrational energy and the vibrational contribution to the entropy and enthalpy at 60 °C. Standard textbook formulas,[27] based on the statistical thermodynamics of an ideal gas, were used for this purpose. The contributions to the enthalpy and entropy from translation and external rotation, as well as the electronic contribution to the entropy, were also calculated using the standard textbook formulas. For details of these formulas, the reader is referred to the cited textbooks[27] and also the Supporting Information of a recent publication in this journal.[16]

In the previous calculations of the equilibrium constant,[15] the harmonic oscillator approximation was adopted, and hence, the low-frequency torsional modes were treated as vibrations.[28] However, it is well-known that this approximation can sometimes introduce error to the calculations, though errors of less than an order of magnitude in rate coefficients have been reported for radical addition reactions.[29−32] Nonetheless, a more sophisticated treatment of the low frequency (<300 cm^{-1}) torsional modes has been adopted for the monosubstituted systems of the present work. For each mode, the full rotational potential was first calculated at the B3-LYP/6-31G(d) level of theory by scanning through 360° in steps of 10°. In keeping with previous recommendations,[30] relaxed (rather than frozen) scans were used. The contribution of these modes to the total entropy and enthalpy were then calculated using standard methods, as follows. For those modes having rotational potentials that could be described by a simple cosine function, the tables of Pitzer and co-workers[33,34] were used. For the more complex modes, the rotational potentials were fitted with a Fourier series of up to 18 terms, and the corresponding energy levels were found numerically by solving the one-dimensional Schrödinger for a rigid rotor, using a Fortran program described previously.[32,35] It should be noted that this more general method yields results that are identical to those of the Pitzer tables for the special case of rotational potentials that can be described via a simple cosine function.

To assist in the qualitative rationalization of the results, the radical stabilization energies (RSEs) of various model radicals were also calculated, including: $^\bullet CH_2{-}Z$ (Z = CH_3, phenyl, benzyl), $^\bullet CH_2S{-}R$ (R = CH_3, benzyl, CH_2COOCH_3, $C(CH_3)_2CN$), and $^\bullet R$. The RSE of a radical $X^\bullet$ is defined as the energy change of the isodesmic reaction, $X^\bullet + CH_4 \rightarrow XH + CH_3^\bullet$, with the

Table 1. Thermodynamics at 333 K of the Addition−Fragmentation Equilibrium, $CH_3SC(Z){=}S + {}^{\bullet}R \rightarrow CH_3SC^{\bullet}(Z)S{-}R$, for the Monosubstituted Systems[a]

product radical[b]	Z	R	ΔH_0, kJ mol^{-1}	ΔH_{333}, kJ mol^{-1}	ΔS_{333}, J mol^{-1} K^{-1}	ΔG_{333}, kJ mol^{-1}	K_{333}, L mol^{-1}
1	CH_3	CH_3	−64.2	−67.6	−118.7	−28.0	6.8×10^5
2	phenyl	CH_3	−95.2	−98.8	−110.1	−62.1	1.5×10^{11}
3	benzyl	CH_3	−72.3	−75.0	−99.7	−41.7	9.6×10^7
4	CH_3	benzyl	−34.2	−30.7	−108.5	5.4	3.9
5	CH_3	CH_2COOCH_3	−58.1	−52.5	−128.1	−9.8	9.4×10^2
6	CH_3	$C(CH_3)_2CN$	−33.9	−30.5	−155.0	21.1	1.3×10^{-2}

[a] The reaction enthalpy at 0 K (ΔH_0) was calculated at the G3(MP2)-RAD level of theory, and includes scaled B3-LYP/6-31G(d) zero-point vibrational energy contributions. The reaction enthalpy at 333 K (ΔH_{333}) was obtained by adding thermal correction to the enthalpy at 333 K to ΔH_0. The thermal correction, and also the entropy at 333 K (ΔS_{333}), were both calculated at the B3-LYP/6-31G(d) level using standard formulas, based on the statistical thermodynamics of an ideal gas. In implementing these formulas, the low-frequency torsional modes were treated as hindered internal rotations. The equilibrium constant was calculated as $K = V^{\circ} \exp(-\Delta G/RT)$, where V° was the basis volume (1 mol of ideal gas at 333 K, $V^{\circ} = 27.337$ L mol^{-1}) used in calculating ΔS_{333}, and the Gibb's free energy (ΔG_{333}) is given by the standard formula, $\Delta G = \Delta H - T\Delta S$. For further details, see text. [b] See Figure 1.

${}^{\bullet}CH_3$ radical providing the reference point. The RSEs were calculated at 0 K and, as in the case of the reaction enthalpies, the RSEs were calculated at the G3(MP2)-RAD//B3-LYP/6-31G(d) level of theory and include B3-LYP/6-31G(d) zero-point energy corrections. For three of the radicals (${}^{\bullet}CH_2CH_3$, ${}^{\bullet}CH_2Ph$, and ${}^{\bullet}CH_2COOCH_3$), previously published RSEs (obtained at the same level of theory) were taken directly from an earlier study,[36] though the relevant B3-LYP/6-31G(d) geometries were calculated and are included in the Supporting Information of the present work for the sake of completeness.

3. Results and Discussion

Monosubstituted Systems. To explore the effect of individual substituents on the addition−fragmentation equilibrium in RAFT polymerization, $R^{\bullet} + S{=}C(Z)SCH_3 \rightarrow R{-}SC^{\bullet}(Z)SCH_3$, equilibrium constants at 60 °C were calculated for the monosubstituted systems: $R = CH_3$ with $Z = CH_3$, phenyl, and benzyl and also $Z = CH_3$ with $R =$ benzyl, CH_2COOCH_3, and $C(CH_3)_2CN$ (see Table 1). Also included in Table 1 are the corresponding reaction enthalpies at 0 and 333 K, together with the change in the entropy and in the Gibb's free energy at 333 K for each reaction. The geometries of RAFT-adduct radicals are illustrated schematically in Figure 1, whereas those of the various reactants are provided in Figure 2. Full geometries in the form of Gaussian archive entries are provided in Table S1 of the Supporting Information.

Examining these data, it is apparent that the equilibrium constant is extremely sensitive to both the R and Z substituents, varying by 13 orders of magnitude over the six reactions considered. As seen previously, the reactions with the methyl R groups have very high equilibrium constants, and, within this series, the phenyl-substituted RAFT agent has a considerably higher equilibrium constant than the benzyl-substituted RAFT agent. Both have higher equilibrium constants than the reaction with the methyl-substituted agent. The RAFT agents with nonmethyl R groups have considerably lower equilibrium constants, the $C(CH_3)_2$-CN R group giving the lowest equilibrium constant and the CH_2COOCH_3 R group giving the highest. A previous kinetic study showed that rate retardation becomes significant when the equilibrium constant exceeds 10^6–10^7 L mol^{-1}.[9] On this basis, the RAFT agents with phenyl and benzyl substituents in the Z position (but with methyl R groups) should show strong rate retardation, whereas those with a methyl group in the Z position should not. However, it is clear that RAFT agents with more realistic R groups have equilibrium constants that are considerably lower than those with methyl R groups. Hence, it is possible that the use of nonmethyl R groups on phenyl- or benzyl-substituted RAFT agents could relieve this rate retardation. To establish whether slow fragmentation contributes to rate retardation in real RAFT systems, it is thus necessary to consider the effects of the R and Z substituents acting in combination, and these will be considered in the following section.

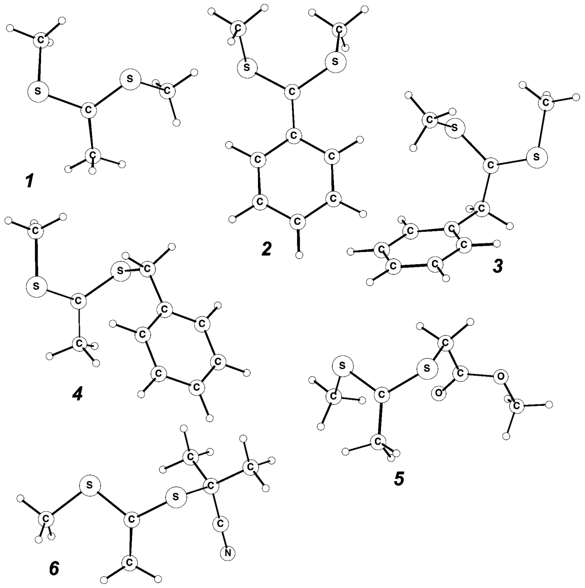


Figure 1. B3-LYP/6-31G(d) optimized geometries for the minimum energy conformations of the RAFT-adduct radicals for the monosubstituted systems: $CH_3SC^{\bullet}(CH_3)S{-}CH_3$ (1), $CH_3SC^{\bullet}(Ph)S{-}CH_3$ (2), $CH_3SC^{\bullet}(CH_2Ph)S{-}CH_3$ (3), $CH_3SC^{\bullet}(CH_3)S{-}CH_2Ph$ (4), $CH_3SC^{\bullet}(CH_3)S{-}CH_2COOCH_3$ (5), and $CH_3SC^{\bullet}(CH_3)S{-}C(CH_3)_2CN$ (6).

The results for the monosubstituted systems can help to provide an insight into the effects of the R and Z substituents on the addition−fragmentation equilibrium. If we focus first on the reaction enthalpies, the trends in the enthalpies generally follow those expected on the basis of radical-stabilization arguments. To provide a qualitative guide to the effects of the R and Z substituents on the stability of the RAFT-adduct radical and (in the case of R) the attacking radical, various radical stabilization energies (RSEs) were calculated (see Table 2). In particular, to examine the effect of the Z substituent on the stability of the adduct, the RSEs of the ${}^{\bullet}CH_2{-}Z$ ($Z = CH_3$, phenyl, benzyl) radicals were calculated, whereas to examine the effect of the R

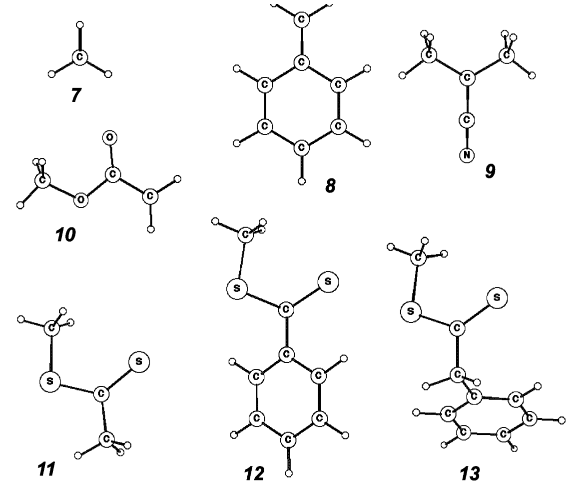


Figure 2. B3-LYP/6-31G(d) optimized geometries for the minimum energy conformations of the products of β-scission of the various RAFT-adduct radicals: $^\bullet CH_3$ (7), $^\bullet CH_2Ph$ (8), $^\bullet C(CH_3)_2CN$ (9), $^\bullet CH_2COOCH_3$ (10), $S{=}C(CH_3)SCH_3$ (11), $S{=}C(Ph)SCH_3$ (12), and $S{=}C(CH_2Ph)SCH_3$ (13).

Table 2. Radical Stabilization Energies (RSEs, 0 K, kJ mol^{-1})[a] of Model Radicals

effect of Z on adduct		effect of R on adduct		effect of R on R$^\bullet$	
model	RSE	model	RSE	model	RSE
$^\bullet CH_2(CH_3)$	14.1[b]	$^\bullet CH_2SCH_3$	40.7	$^\bullet CH_3$	0.0
$^\bullet CH_2(Ph)$	58.9[b]	$^\bullet CH_2SCH_2Ph$	37.9	$^\bullet CH_2Ph$	58.9[b]
$^\bullet CH_2(Bz)$	10.6	$^\bullet CH_2SCH_2COOCH_3$	36.6	$^\bullet CH_2COOCH_3$	21.5[b]
		$^\bullet CH_2SC(CH_3)_2CN$	35.0	$^\bullet C(CH_3)_2CN$	59.0

[a] The RSE of a radical $X^\bullet$ is defined as the energy of the isodesmic reaction: $X^\bullet + CH_4 \rightarrow XH + {}^\bullet CH_3$. The RSEs were calculated at the G3(MP2)-RAD level of theory and include scaled B3-LYP/6-31G(d) zero-point vibrational energy contributions. [b] From ref 36.

substituent on the stability of the adduct, the RSEs of $^\bullet CH_2S{-}R$ (R = CH_3, benzyl, CH_2COOCH_3, $C(CH_3)_2CN$) were obtained. The RSEs of the $^\bullet R$ attacking radicals were also calculated.

Examining the RSEs (Table 2), we first note that the Z substituent is expected to have a strong effect on the stability of the RAFT-adduct radical at it is directly attached the carbon bearing the unpaired electron. We also note that the phenyl substituent is expected to stabilize the adduct to a greater degree, due its ability to delocalize the unpaired electron onto the aromatic ring. As a result, the addition reaction is expected to be more exothermic for the phenyl-substituted RAFT agent, than for the benzyl- and methyl-substituted cases, and this is indeed the case. However, other factors are required to explain the smaller difference in enthalpy between benzyl- and methyl-substituted agents. For these cases, we note that the reaction with benzyl-substituted RAFT agent is more exothermic than that of the methyl-substituted agent, despite the (marginally) greater radical-stabilizing ability of the methyl substituent. It is important to realize the Z substituent also affects the stability of the RAFT agent and, in this case, the greater exothermicity of the addition reaction for the benzyl-substituted agent may reflect a greater release of steric strain upon reaction.

Turning our attention to the R substituent, we first note that it does not show a substantial effect on the stability of the RAFT adduct radical, as it is insulated from the unpaired electron by the intervening sulfur atom. This can be seen in Table 2, where the RSEs of the $^\bullet CH_2SR$ radicals vary over a relatively narrow range, despite the wide-ranging electronic properties of the R groups. As a result, we would expect that the effect of the R group on the enthalpy for the addition reaction is dominated by the stability of the attacking $R^\bullet$ radical. As the RSEs indicate, the benzyl and $^\bullet C(CH_3)_2CN$ radicals are both relatively stable radicals, the $^\bullet CH_2COOCH_3$ radical is considerably less stable, and the $^\bullet CH_3$ radical is the least stable of the attacking radicals. As a result, one would expect the R = CH_3 system to have the greatest exothermicity, the R = CH_2COOCH_3 system to have the next largest, and the R = $C(CH_3)_2CN$ and R = benzyl systems to have the smallest exothermicities. If we examine Table 1, we find that this is indeed the case, and hence, the substituent effects follow the trends in the stability of the $R^\bullet$ radical.

If we now focus on the reaction entropies, we find that steric effects also play a role in these reactions. In general, the bulkier the Z substituent, the *less* exentropic the reaction. This may reflect a release of steric strain upon reaction and might be understood in terms of the greater flexibility when the Z substituent is attached to the $C^\bullet$ center of the RAFT-adduct radical, compared to when it is attached to the corresponding C=S double bond of the RAFT agent. By contrast, the bulkier the R group, the *more* exentropic the reaction, which may reflect the increased crowding as the attacking $R^\bullet$ radical forms a bond to the sulfur atom of the RAFT agent. These steric effects play an important role in determining the overall equilibrium constant and can, for example, explain why the equilibrium constant for the R = benzyl system is much smaller than that for the R = $C(CH_3)_2CN$, despite their similar radical stabilities and reaction exothermicities.

At this point, it is worth comparing the results of this study with a recent experimental survey of substituent effects in RAFT polymerization.[37,38] This previous survey focused on the transfer constant of a given RAFT agent, which is in turn a function of the forward (k_{add}) and reverse (k_{-add}) rates of addition to the initial agent, as well as the fragmentation rate (k_β)

$$k_{tr} = k_{add}\frac{k_\beta}{k_{-add} + k_\beta} \tag{4}$$

It should be noted that eq 4 is actually only valid if the steady-state assumption holds, if the adduct does not undergo side reactions, and if the fragmentation reaction is irreversible. In real polymerizations, the relationship between the observed transfer constant and the individual reactions would be more complex. Although this previous study focused on different aspects of the addition−fragmentation reaction, many of the conclusions are similar to those of the present work. In particular, it was noted that fragmentation was favored by R groups with increased radical stability, greater steric bulk, and increased electrophilicity, and this is in accord with the observations in the present study. The previous work also noted that the reactivity of the RAFT agent was greater for phenyl-substituted agents compared to alkyl-substituted RAFT agents, and this is also seen in the present case. However, this previous work stressed that the radical stabilization ability of a Z substituent is not by itself a predictive tool in estimating transfer coefficients. In particular, they highlighted the role that resonance plays in stabilizing

Table 3. Thermodynamics at 333 K of the Addition−Fragmentation Equilibrium, $CH_3SC(Z)=S + {}^•R \rightarrow CH_3SC^•(Z)S-R$, for the Disubstituted Systems[a]

product radical[b]	Z	R	ΔH_0, kJ mol^{-1}	ΔH_{333}, kJ mol^{-1}	ΔS_{333}, J mol^{-1} K^{-1}	ΔG_{333}, kJ mol^{-1}	K_{333}, L mol^{-1}
14	benzyl	benzyl	−51.5	−50.0	−143.2	−2.3	6.3×10^1
15	phenyl	benzyl	−78.1	−77.0	−144.8	−28.8	8.8×10^5
16	benzyl	CH_2COOCH_3	−59.0	−58.9	−160.7	−5.4	1.9×10^2
17	phenyl	CH_2COOCH_3	−81.8	−81.2	−153.5	−30.1	1.5×10^6
18	benzyl	$C(CH_3)_2CN$	−46.0	−46.3	−182.0	14.3	1.6×10^{-1}
19	phenyl	$C(CH_3)_2CN$	−70.1	−71.1	−191.5	−7.3	3.8×10^2

[a] The reaction enthalpy at 0 K (ΔH_0) was calculated at the RMP2/6-311+G(3df,2p) level of theory and includes scaled B3-LYP/6-31G(d) zero-point vibrational energy contributions. The reaction enthalpy at 333 K (ΔH_{333}) was obtained by adding thermal correction to the enthalpy at 333 K to ΔH_0. The thermal correction, and also the entropy at 333 K (ΔS_{333}), were both calculated at the B3-LYP/6-31G(d) level using standard formulas, based on the statistical thermodynamics of an ideal gas. In implementing these formulas, the harmonic oscillator approximation was used. The equilibrium constant was calculated as $K = V^\circ \exp(-\Delta G/RT)$, where V° was the basis volume (1 mol of ideal gas at 333 K, $V^\circ = 27.337$ L mol^{-1}) used in calculating ΔS_{333}, and the Gibb's free energy (ΔG_{333}) is given by the standard formula, $\Delta G = \Delta H - T\Delta S$. For further details, see text. [b] See Figure 3.

the C═S bond of RAFT agents bearing O-alkyl and *N*,*N*-dialkyl Z substituents. These substituents were not included in the present work, but the same reduced reactivity has been noted in a previous theoretical study of xanthate polymerization.[16] Hence, the role of the Z substituent in modifying the stability of the thiocarbonyl compound, as well as the RAFT-adduct radical, are both important factors in governing the reactivity of the addition−fragmentation equilibrium.

Disubstituted Systems. The equilibrium constants at 60 °C for the addition−fragmentation equilibrium, $R^• + S{=}C(Z)SCH_3 \rightarrow R{-}SC^•(Z)SCH_3$, were calculated for the disubstituted systems: R = benzyl, CH_2COOCH_3, or $C(CH_3)_2CN$, with Z = phenyl and benzyl (see Table 3). The corresponding reaction enthalpies, entropies, and Gibb's free energies are also included in Table 3. The geometries of RAFT-adduct radicals are illustrated schematically in Figure 3, and full geometries in the form of Gaussian archive entries are provided in Table S1 of the Supporting Information.

Examining Table 3, we find that the equilibrium constant is again very sensitive to both the R and Z substituents, with a variation of 7 orders of magnitude among the six reactions considered. As with the monosubstituted systems, the RAFT agents having the radical-stabilizing phenyl group in the Z position have significantly higher equilibrium constants than the corresponding benzyl-substituted RAFT agents, and the reactions with the $^•CH_2COOCH_3$ radical have considerably higher equilibrium constants than the corresponding reactions with the more stable $^•C(CH3)_2CN$ radical. However, in contrast to the monosubstituted systems, the difference in equilibrium constants between corresponding R = CH_2COOCH_3 and benzyl substituted systems is considerably smaller, despite the large differences in the stabilities of the $R^•$ radical. There thus appears to be some degree of synergism in the effects of the R and Z substituents on the relative stability of the product radical. This is despite the fact that the radical stabilization energies in Table 2 indicated that the R group in isolation should not substantially affect the stability of the adduct. The origin of these synergistic effects is difficult to establish at the present time, but they may arise through sterically induced conformational changes in the RAFT adduct when R and Z are both bulky substituents, or some through the form of cooperative polar interaction in the RAFT adduct radical.

A second important observation that can be made from Table 3 is that the results appear to support the idea that slow fragmentation is responsible for rate retardation in certain RAFT polymerization systems. The reactions having a phenyl group in the Z position and either a benzyl or a CH_2COOCH_3 R group have equilibrium constants of approximately 10^6. As was demonstrated in a previous kinetic study of RAFT polymerization, equilibrium constants of this magnitude are sufficient to explain rate retardation without recourse to additional side reactions.[9] Hence, these two reactions, which model the *polymeric* addition−fragmentation equilibrium in the CDB-mediated polymerization of styrene and methyl acrylate, respectively, are predicted to show rate retardation at 60 °C. The calculated equilibrium constants are within 1 order of magnitude of the experimental values estimated from molecular weight data (which are based on the assumption that *all* rate retardation is due to slow fragmentation) but differ by 5 orders of magnitude from the

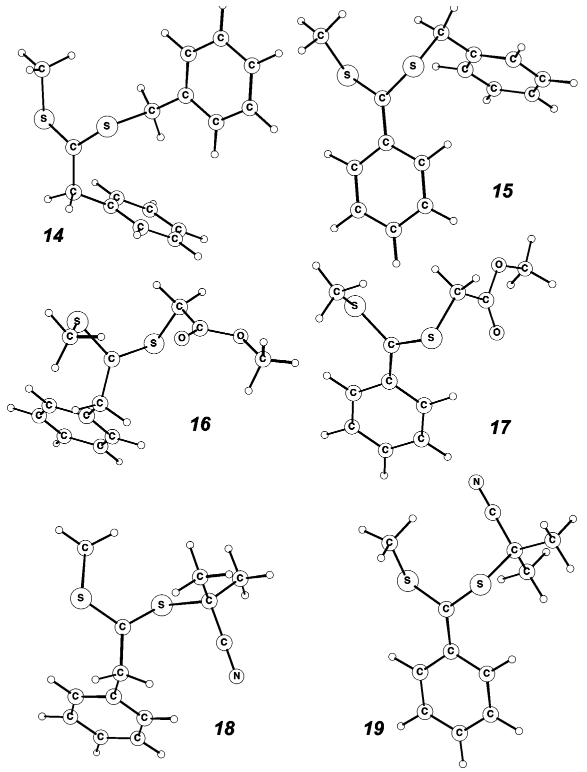


Figure 3. B3-LYP/6-31G(d) optimized geometries for the minimum energy conformations of the RAFT-adduct radicals for the disubstituted systems: $CH_3SC^•(CH_2Ph)S-CH_2Ph$ (14), $CH_3SC^•(Ph)S-CH_2Ph$ (15), $CH_3SC^•(CH_2Ph)S-CH_2COOCH_3$ (16), $CH_3SC^•(Ph)S-CH_2COOCH_3$ (17), $CH_3SC^•(CH_2Ph)S-C(CH_3)_2CN$ (18), and $CH_3SC^•(Ph)S-C(CH_3)_2CN$ (19).

Table 4. Accuracy of the Harmonic Oscillator Approximation for the Equilibrium Constant[a] of the Monosubstituted Systems, $CH_3SC(Z){=}S + {}^{\bullet}R \rightarrow CH_3SC^{\bullet}(Z)S{-}R$

product radical[b]	Z	R	hindered rotor	harmonic oscillator	error[c]
1	CH_3	CH_3	6.8×10^5	1.4×10^5	4.9
2	phenyl	CH_3	1.5×10^{11}	2.4×10^9	63.1
3	benzyl	CH_3	9.6×10^7	2.7×10^6	35.8
4	CH_3	benzyl	3.9	7.7×10^{-2}	50.4
5	CH_3	CH_2COOCH_3	9.4×10^2	7.3×10^1	13.0
6	CH_3	$C(CH_3)_2CN$	1.3×10^{-2}	1.7×10^{-3}	7.9

[a] Hindered rotor equilibrium constants (333 K, L mol^{-1}) were calculated as described in footnote *a* of Table 1. The corresponding harmonic oscillator values were calculated using the same computational methods but the harmonic oscillator approximation was used in treating the low-frequency torsional modes. It should be noted that the harmonic oscillator values for the $R = CH_3$ with $Z = $ phenyl and $Z = $ benzyl differ slightly from those in ref 15 as the free rotor model was used to treat some of the low-frequency torsional modes in this previous work. [b] See Figure 1. [c] Defined as the hindered rotor value divided by the corresponding harmonic oscillator value.

experimental values estimated from ESR data (which, through the quasi-steady-state assumption, are based on the assumption that *no* rate retardation is due to slow fragmentation). As will now be demonstrated, within the possible error in the data, these calculations can support the higher experimental values of the equilibrium constant but not the lower values. These possible sources of error are as follows.

First, there is the error in the calculations associated with the computational methods used. Although high-level composite methods were used to study the monosubstituted systems, a slightly lower level of theory was used for the larger disubstituted systems. Based on a previous assessment study,[25] the likely errors in the absolute reaction enthalpies at this level of theory could contribute to an uncertainty of approximately 1 order of magnitude in the equilibrium constant at 60°C. In addition, although the hindered rotor method was used for monosubstituted systems, the harmonic oscillator approximation was used in calculating the larger disubstituted systems. The additional errors in the equilibrium constants arising from the harmonic oscillator approximation can be established by comparing the corresponding harmonic oscillator and hindered rotor values for the monosubstituted systems (see Table 4). From Table 4, it is seen that the harmonic oscillator values serve as a lower bound to the more accurate hindered rotor values. Not surprisingly, the error is larger for the more complicated systems, as these have additional low frequency torsional modes. For the more complex systems (which provide the best indication of the errors in the disubstituted systems), the error is nearly 2 orders of magnitude. It is therefore clear that the calculated equilibrium constants in Table 3 for the disubstituted systems serve as lower bounds to the true equilibrium constants for these model reactions, with the true values being *higher* by 1−2 orders of magnitude.

Second, there is the question of whether the calculated equilibrium constants, which correspond to a model reaction in the gas phase, have relevance for solution-phase polymerization systems. Examining first the issue of solvent effects, the main difference between the gas-phase and solution-phase values for these reactions arises in entropic factors. In the gas-phase, the reactants and product have translational and rotational entropy, whereas in the solution-phase, this entropy is effectively “lost” in collisions with the solvent. In place of the translational and rotational motion, the solution-phase molecules have additional “vibrational” degrees of freedom, corresponding to their interaction with the solvent. However, these additional vibrational modes generally contribute less to the total entropy of a molecule than the corresponding translational and rotational modes in the gas-phase. This difference between the gas-phase and solution-phase entropy is significant in a bimolecular reaction, because three translational and three rotational modes are converted to internal modes on reaction. Since these lost modes contribute less to the total entropy in the solution phase, the solution-phase reaction is expected to be less exentropic than the corresponding gas-phase reaction, and thus it should have a *larger* equilibrium constant. Clear evidence for this “entropic” solvent effect can be found in comparisons of corresponding *experimental* gas-phase and solution-phase rate coefficients for radical addition to alkenes. In these cases, the solution-phase rate coefficients generally exceed the gas-phase values by an order of magnitude.[39] To summarize, the calculated gas-phase rate coefficients should serve as lower bounds to corresponding solution-phase values, which might reasonably be expected to exceed the calculated values by an order of magnitude.

The second important issue is whether the simplified chemical model used in the present work can represent the polymeric addition−fragmentation equilibrium in CDB-mediated polymerization of styrene and methyl acrylate. There are two main differences between the model system and the real system. The first is that, to use a high level of theory, the nonparticipating group on the RAFT agent is modeled using a methyl group. It has been noted previously that this nonparticipating group should not exert a substantial influence on the addition reaction as it is insulated from the reaction center by the intervening sulfur atom.[37] The synergistic effects between the attacking R group and the Z substituent that have been observed in the present work suggest that there may be some error in modeling the nonparticipating group as a methyl substituent. Nonetheless, unlike the interactions involving the Z substituent with the *attacking* $R^{\bullet}$ radical, the interactions involving the nonparticipating group are likely to be present in both the reactant RAFT agent and the product RAFT-adduct radical. As result, such interactions might reasonably be expected to cancel (to a large extent) from the equilibrium constant, and hence, the error in using a methyl group as the *nonparticipating group* should be expected to be relatively small.

The other, more significant, approximation in the present work is the truncation of the *attacking* polymeric propagating radicals at the alpha position, neglecting both chain length effects and penultimate unit effects. Although the penultimate unit effects in these cases might be expected to be small (i.e., less than an order of magnitude), the chain length effects are expected to be somewhat larger. It is known that steric effects are important in determining the leaving group ability, and that oligomeric or polymeric radicals might be expected to be better leaving groups than primary radicals.[37] Indeed, a recent analysis based on chain transfer constants suggested that the polymeric leaving radical in methyl methacrylate polymerization should fragment 160 times faster than the corresponding unimer radical.[8] Hence, the neglect of chain length effects may be contributing to an overestimation of the equilibrium constant by approximately 2 orders of magnitude.

Combining these various sources of error, we note that the neglect of solvent effects and the use of the harmonic oscillator approximation contribute to an *underestimation* of the equilibrium constant by approximately 2−3 orders of magnitude, whereas the neglect of chain length effects contributes to *overestimation* by approximately 2 orders of magnitude. These errors thus oppose each other, and one might expect the calculated values to provide a reasonable indication of the magnitude of the equilibrium constant in free-radical polymerization, within a tolerance of 1−2 orders of magnitude. Thus, as noted above, the calculated values support the large equilibrium constants obtained using the assumption that *all* rate retardation is due to slow fragmentation but not the small equilibrium constants obtained using the quasi-steady-state assumption. Further calculations, using the hindered rotor model and considering the effects of the solvent and chain length, are required to determine the exact extent to which slow fragmentation causes rate retardation. Nonetheless, the present results add weight to the idea that the cross-termination reaction is not primary cause of rate retardation in RAFT polymerization and occurs (at high RAFT agent concentrations) as a consequence of the long lifetime of the adduct.

Finally, as further support for the relevance of these results for real polymerization systems, it can be seen that the results for the other four reactions are also consistent with experimental observations. First, it is seen that the reactions with a benzyl substituent in the Z position have equilibrium constants that are significantly lower than 10^6 L mol^{-1} and hence should not be expected to show rate retardation. This is in accord with the experimental observation that the rate retardation in polymerizations of styrene and methyl acrylate is relieved with the phenyl Z substituent in CDB is replaced with a benzyl group (as in cumyl phenyl dithioacetate[17,18]). Second, even with a phenyl group in the Z position, the equilibrium constant for the $^{\bullet}C(CH_3)_2$-CN radical is considerably lower than 10^6 L mol^{-1} and is not predicted to cause rate retardation. This is consistent with the experimental observation that the inhibition period (associated with the addition−fragmentation equilibrium of the initial RAFT agent) is relieved when the cumyl group of CDB is replaced with a $C(CH_3)_2CN$ group.[19]

4. Conclusions

High-level ab initio molecular orbital calculations of the addition−fragmentation equilibrium constants in model RAFT reactions indicate that slow fragmentation of the polymeric RAFT-adduct radical is responsible for rate retardation in cumyl dithiobenzoate mediated polymerization of styrene and methyl acrylate. Although the calculations correspond to a model reaction in the gas phase, a detailed error analysis indicates that the calculated values should be indicative of real polymer systems. As further support for this, the calculations also reproduce the experimental observations that rate retardation is relieved by changing the phenyl Z substituent of a RAFT agent to a benzyl group and that inhibition is relieved when a $C(CH_3)_2CN$ leaving group is included in the RAFT agent.

The calculations also provide an insight into the effects of substituents on the addition−fragmentation equilibrium. It is clear from the calculations that the equilibrium constant is extremely sensitive to the nature of both the Z and the R substituents, with a 13 orders of magnitude variation over the 12 reactions considered. The effects of these substituents on the reaction enthalpy are in general accord with the trends expected on the basis of radical stabilization arguments. However, there are additional steric effects on the reaction entropy and certain synergistic effects between the R and Z substituents on the stability of the RAFT-adduct radicals, which affect the trends in the equilibrium constants. These highlight the complexity of the RAFT process, and but also the scope we have for modifying the reactivity of RAFT agents to control a wide range of monomers.

Acknowledgment. Generous allocations of computing time on the Compaq Alphaserver and the Linux Cluster of the Australian Partnership for Advanced Computing and the Australian National University Supercomputer Facility, useful discussions with Professor Leo Radom, and provision of an Australian Research Council postdoctoral fellowship are all gratefully acknowledged.

Supporting Information Available: Table S1 shows the B3-LYP/6-31G(d) optimized geometries (in the form of GAUSSIAN archive entries) for species 1−19 in Figures 1−3, together with the additional radicals and corresponding closed-shell species used in calculating the radical stabilization energies of Table 2. This material is available free of charge via the Internet at http://pubs.acs.org.

References and Notes

(1) Hawker, C. J.; Bosman, A. W.; Harth, E. *Chem. Rev.* **2001**, *101*, 3661−3688.
(2) Wang, J. S.; Matyjaszewski, K. *J. Am. Chem. Soc.* **1995**, *117*, 5614−5615.
(3) 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.
(4) Kwak, Y.; Goto, A.; Tsuji, Y.; Murata, Y.; Komatsu, K.; Fukuda, T. *Macromolecules* **2002**, *35*, 3026−3029.
(5) Barner-Kowollik, C.; Quinn, J. F.; Morsley, D. R.; Davis, T. P. *J. Polym. Sci. A Polym. Chem.* **2001**, *39*, 1353−1365.
(6) Barner-Kowollik, C.; Coote, M. L.; Davis, T. P.; Radom, L.; Vana, P. *J. Polym. Sci. A Polym. Chem.* **2003**, *41*, 2828−2832.
(7) Wang, A. R.; Zhu, S.; Kwak, Y.; Goto, A.; Fukuda, T.; Monteiro, M. S. *J. Polym. Sci. A* **2003**, *41*, 2833−2839.
(8) Kwak, Y.; Goto, A.; Fukuda, T. *Macromolecules* **2004**, *37*, 1219−1225.
(9) Vana, P.; Davis, T. P.; Barner-Kowollik, C. *Macromol. Theory Simul.* **2002**, *11*, 823−835.
(10) Calitz, F. M.; Tonge, M. P.; Sanderson, R. D. *Macromol.* **2003**, *36*, 5−8.
(11) Barner-Kowollik, C.; Vana, P.; Quinn, J. F.; Davis, T. P. *J. Polym. Sci. A Polym. Chem.* **2002**, *40*, 1058−1063.
(12) Monteiro, M. J.; de Brouwer, H. *Macromolecules* **2001**, *34*, 349−352.
(13) Ah Toy, A.; Vana, P.; Davis, T. P.; Barner-Kowollik, C. *Macromolecules* **2004**, *37*, 744−751.
(14) Calitz, F. M.; McLeary, J. B.; McKenzie, J. M.; Tonge, M. P.; Klumperman, B.; Sanderson, R. D. *Macromol.* **2003**, *36*, 9687−9690.
(15) Coote, M. L.; Radom, L. *J. Am. Chem. Soc.* **2003**, *125*, 1490−1491.
(16) Coote, M. L.; Radom, L. *Macromolecules* **2004**, *37*, 590−596.
(17) Barner-Kowollik, C.; Quinn, J. F.; Uyen Nguyen, T. L.; Heuts, J. P. A.; Davis, T. P. *Macromolecules* **2001**, *34*, 7849−7857.
(18) Quinn, J. F.; Rizzardo, E.; Davis, T. P. *Chem. Commun.* **2001**, 1044−1045.

(19) Perrier, S.; Barner-Kowollik, C.; Quinn, J. F.; Vana, P.; Davis, T. P. *Macromolecules* **2002**, *35*, 8300−8306.
(20) Hehre, W. J.; Radom, L.; Schleyer, P. v. R.; Pople, J. A. *Ab Initio Molecular Orbital Theory*; Wiley: New York, 1986.
(21) Koch, W.; Holthausen, M. C. *A Chemist's Guide to Density Functional Theory*; Wiley-VCH: Weinheim, Germany, 2000.
(22) 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.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*; Gaussian, Inc.: Pittsburgh, PA, 1998.
(23) 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, U.K., 1999
(24) Henry, D. J.; Sullivan, M. B.; Radom, L. *J. Chem. Phys.* **2003**, *118*, 4849−4860.
(25) Coote, M. L.; Wood, G. P. F.; Radom, L. *J. Phys. Chem. A* **2002**, *106*, 12124−12138.
(26) Scott, A. P.; Radom, L. *J. Phys. Chem.* **1996**, *100*, 16502−16513.
(27) See, for example: (a) Stull, D. R.; Westrum, E. F., Jr.; Sinke, G. C. *The Thermodynamics of Organic Compounds*; John Wiley & Sons: New York, 1969. (b) Robinson, P. J. *J. Chem. Ed.* **1978**, *55*, 509−510. (c) Steinfeld, J. I.; Francisco, J. S.; Hase, W. L. *Chemical Kinetics and Dynamics*; Prentice Hall: Englewood Cliffs, NJ, 1989.
(28) In fact, the free rotor approximation was used in calculating the thermal correction to the enthalpy for some of these modes. This improved the accuracy slightly, but not significantly.
(29) Heuts, J. P. A.; Gilbert, R. G.; Radom, L. *Macromolecules* **1995**, *28*, 8771−8781.
(30) Van Speybroeck, V.; Van Neck, D.; Waroquier, M.; Wauters, S.; Saeys, M.; Martin, G. B. *J. Phys. Chem. A* **2000**, *104*, 10939−10950.
(31) Gómez-Balderas, R.; Coote, M. L.; Henry, D. J.; Radom, L. *J. Phys. Chem. A* **2004**, *108*, 2874−2883.
(32) Heuts, J. P. A.; Gilbert, R. G.; Radom, L. *J. Phys. Chem.* **1996**, *100*, 18997−19006.
(33) Pitzer, K. S.; Gwinn, W. D. *J. Chem. Phys.* **1942**, *10*, 428−440.
(34) Li, J. C. M.; Pitzer, K. S. *J. Phys. Chem.* **1956**, *60*, 466−474.
(35) (a) Nordholm, S.; Bacskay, G. B. *Chem. Phys. Lett.* **1976**, *42*, 253−258. (b) Bacskay, G. B. Unpublished computer program, written in Fortran.
(36) Henry, D. J.; Parkinson, C. J.; Mayer, P. M.; Radom, L. *J. Phys. Chem. A* **2001**, *105*, 6750−6756.
(37) Chong, Y. K.; Krstina, J.; Le, T. P. T.; Moad, G.; Postma, A.; Rizzardo, E.; Thang, S. H. *Macromolecules* **2003**, *36*, 2256−2272.
(38) 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.
(39) Fischer, H.; Radom, L. *Angew. Chem., Int. Ed.* **2001**, *40*, 1340−1371.

MA049444W