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Comparison of Bond Dissociation Energies of Dormant Species Relevant to Degenerative Transfer and Atom Transfer Radical Polymerization

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ABSTRACT: Density functional calculations are reported for the bond dissociation energy (BDE) of a number of dithioacetates, $CH_3C(S)S-R$ and selected dithiobenzoates, $PhC(S)S-R$, of relevance to reversible addition−fragmentation transfer (RAFT) controlled radical polymerization. In comparison with previously reported calculations [Gillies, M. B.; Matyjaszewski, K.; Norrby, P.-O.; Pintauer, T.; Poli, P.; Richard, R. *Macromolecules* **2003**, *36*, 8551−8559] at the same level on corresponding R−X systems (X = Cl, Br, I, N_3, S_2CNMe_2), the results reveal significant steric and polar effects on the BDE. Particularly bulky R groups (*t*Bu, $C(CH_3)_2COOMe$) yield relatively weaker $R-S_2CZ$ (Z = Me, Ph) bonds, such that the radical transfer process to $R'-S_2CZ$ where R′ is less sterically encumbering (e.g., $CH(CH_3)COOMe$) is less favorable, when compared to the same transfer to R′−Cl (or R′−Br). As indicated by an analysis of DFT computed natural charges, electronegative substituents in the α position of the R group (F, OMe, OAc, and also multiple substitution with Cl atoms) reinforce the ionic component of the R−X bond when X is a more electronegative group (i.e., Cl, Br) relative to S_2CZ. Therefore, transfer of these radicals is also disfavored for $R'-S_2CZ$ relative to R′−Cl or R′−Br. These effects rationalize experimental observations and can be used as a guiding tool for the rational design of ATRP initiators and RAFT transfer agents.

Introduction

Controlled/living radical polymerization (CRP) is among the most rapidly developing areas of polymer science.[1,2] It enables preparation of many previously inaccessible macromolecular structures and new generations of advanced materials.[1,3−8] The degree of precision of macromolecular engineering and control of chain topology, composition, and functionality depends on the contribution of chain breaking reactions as well as on efficiency of initiation. Therefore, it is of paramount importance not only to minimize contributions of irreversible chain transfer and chain termination but also to maximize initiation and cross-propagation efficiency in the synthesis of segmented copolymers.

All of the CRP systems employ dynamic equilibration between dormant species and growing radicals which exchange either via reversible activation/deactivation cycles or through the degenerative transfer process.[1,9] The overall rate of propagation depends on the rate constant of propagation and on the proportion of active species, which is related to the corresponding equilibrium constant. The absolute values of the equilibrium constants and rate constants of the constituting reactions can be determined in various ways, from model studies, polymerization kinetics, spectroscopic studies, etc.[10−22] These values depend very strongly on the structure of the catalyst and the capping species and also on the structure of the propagating radicals.

We have recently reported values of the absolute and relative equilibrium constants for the dissociation of alkyl (pseudo)halides (R−X) with structures relevant to dormant/propagating species in atom transfer radical polymerization (ATRP) and other CRP processes.[23] We found tremendous differences in the bond dissociation energies (BDE) between various alkyl halides. For example, relative values of the ATRP equilibrium constants for R−Cl systems modeling chain ends in polymerization of ethylene, vinyl acetate, methyl acrylate, styrene, and acrylonitrile were $K = 4 \times 10^{-10}$, 3×10^{-7}, 1, 16, and 2×10^3, respectively. Thus, taking into account the corresponding rate constants of propagation, one could estimate that if the time needed to accomplish a given conversion of methyl acrylate with a given ATRP catalytic system were 1 h, the same conversion would be reached after 0.5 s for acrylonitrile, 11 h for styrene, 15 years for vinyl acetate, and 170 000 years for ethylene, under otherwise identical conditions. Therefore, entirely different conditions and catalysts must be used for successful ATRP of acrylonitrile, vinyl acetate, and ethylene than for styrene and methyl acrylate.

A conclusion from the previous studies was that the BDE dramatically depends on the nature of X, in the order Cl > Br > N_3 > S_2CNMe_2 ≈ I. For instance, ΔG values for the methyl 2-(pseudo)halopropionate derivatives are 60.4 kcal/mol (Cl), 51.8 kcal/mol (Br), 47.5 kcal/mol (N_3), 32.4 kcal/mol ($S-C(S)-NMe_2$), and 29.0 kcal/mol (I). The relative values of $\Delta\Delta G$ for selected pairs of R groups are little dependent on the nature of X; e.g., the differences between methyl 2-halopropionates and 1-phenylethyl halides were ~1.6 kcal/mol for Cl and Br, 2 kcal/mol for N_3, ~2.6 kcal/mol for I, and ~2.8 kcal/mol for S_2CNMe_2. However, a significant difference was observed for R = *tert*-butyl vs R = 2-propionate. For chloride, bromide, and iodide the relative differences were quite large ($\Delta\Delta G \sim 8$ kcal/mol, corresponding to the ratio of the bond dissociation equilibrium constants $K_{tB}/K_{PR} \sim 10^{-6}$); see Scheme 1. However, for X = S_2CMe_2, the difference was much smaller ($\Delta\Delta G$ = 0.9 kcal/mol, corresponding to the ratio of the equilibrium constants $K_{tB}/K_{PR} \sim 0.2$!). This indicates that BDE for various X may sometimes specifically depend on R.

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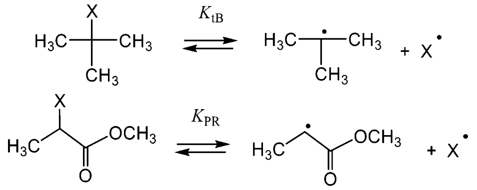
Scheme 1

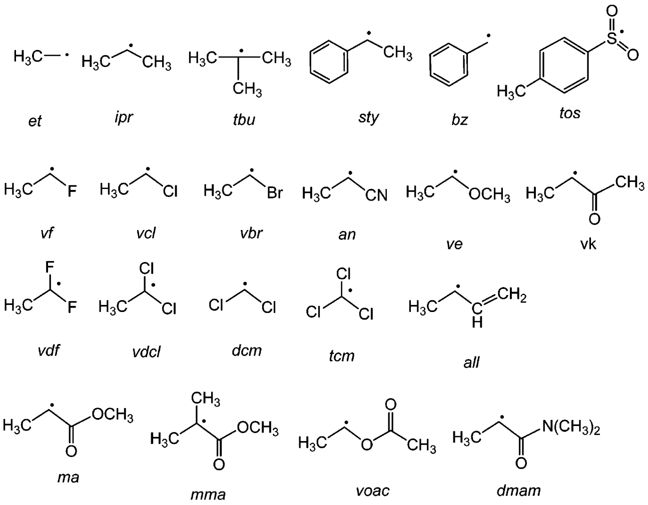


In this paper we present results of calculations for the BDE for a variety of alkyl dithioacetates and for a few selected examples of dithiobenzoates, relevant to reversible addition−fragmentation chain transfer (RAFT) systems, and we compare these values with those previously reported for similar alkyl (pseudo)halides. The BDE values help to understand the effect of R and X structures on the bond strength for the homolytic cleavage (catalyzed or not). They are also important to understand the relative equilibrium position in the exchange reactions during CRP copolymerization processes. It is important to highlight parallel work focused on the substituent effects on the thermodynamics and rates of the radical addition and reverse fragmentation processes involving dithiocarbamate and other substrates.[24−30] In our study, we do not address the individual addition and fragmentation phenomena (i.e., we do not examine the relative energy of the radical addition product), but rather examine the overall radical transfer equilibrium process on the basis of bond dissociation energy calculations, using a wider range of radicals that are closer models of the real polymerization processes. Our study reveals that the trend of BDE for R−SC(S)Me does not perfectly parallel those previously established for analogous R−X series (X = Cl, Br), and it brings to light the steroelectronic reasons for the observed discrepancies.

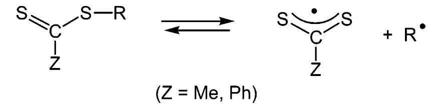
Computational Details

All DFT calculations were run with Gaussian03,[31] using the B3P86 functional.[32] The 6-31G** basis set was used for all H, C, N, O, F, Cl, S, and Br atoms. Since the I atom is not included in the standard 6-31G** basis set, it was described by the LANL2DZdp basis, which includes a relativistic ECP and polarization (d) and diffuse (p) functions.[33] This basis has the efficiency of a core-potential-containing basis set and is believed to provide the accuracy of an all-electron basis set such as 6-31G**. The R and X radicals were optimized with the spin unrestricted formalism; the spin contamination was found to be negligible in all cases. (The mean value of the S^2 operator was always very close to the theoretical value of 0.75.) All geometry optimizations were performed without symmetry constraints (C_1 symmetry). The nature of the resulting stationary points as energy minima was verified by a frequency analysis in each case. All energies were corrected for zero-point vibrational energy and for thermal energy to obtain the bond dissociation enthalpies at 298 K. A spin−orbit correction was also applied for X = Cl, Br, and I as described in our previous contribution.[23] A further entropy correction was applied to obtain the Gibbs free energy at 298 K. The calculations used the standard approximations for estimating the thermochemical corrections (ideal gas, rigid rotor, and harmonic oscillator). The atomic charges were calculated using the natural population analysis (NPA).[34]

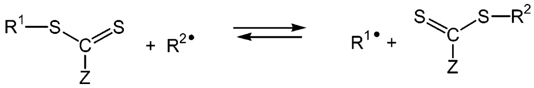
Scheme 2



Scheme 3



Scheme 4



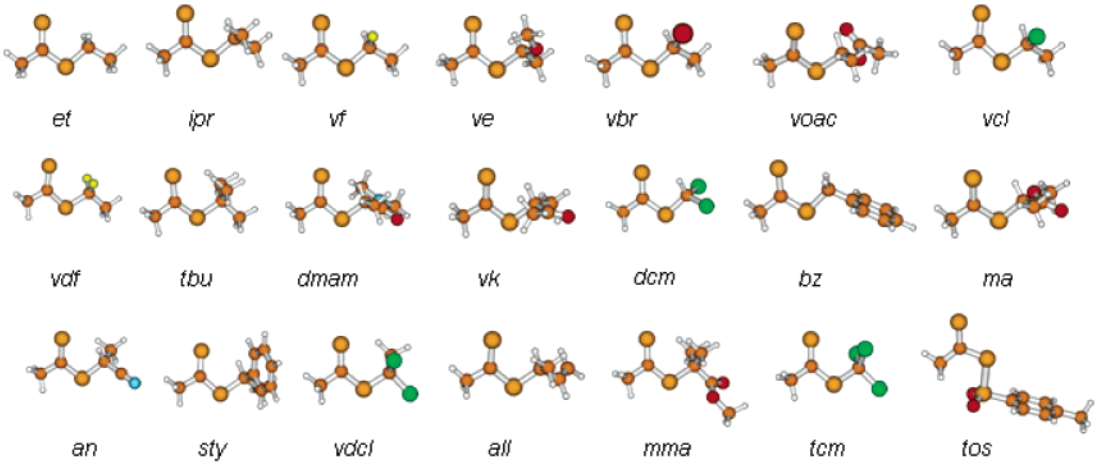
Results

The systems chosen for more detailed investigation are the dithioacetate $CH_3C(S)(SR)$, where R covers the entire range of radicals previously investigated by us to estimate the BDE of R−X (X = Cl, Br, I, N_3, S_2CNMe_2), plus the 1,1-dichloroethyl (*vdcl*) radical. They are shown, together with their abbreviation, in Scheme 2. In addition, a selected list of dithiobenzoates, $C_6H_5C(S)(SR)$, was also calculated.

The calculations were carried out at the same computational level as previously used to obtain the energies and thermochemical data for the R radicals and for the other R−X molecules,[23] namely using DFT with the BP86 functional and basis sets at the 6-31G** level for all atoms. The new data presented in this contribution cannot be directly compared with experimental thermochemical data since these do not appear to be available, but we have shown earlier that this computational level provides BDEs in quite good agreement with the experiment for R−X (X = Cl, Br, I) compounds. In combination with the previous calculations for the free radicals, the new results provide BDE's for the R−SC(S)Z (Z = Me, Ph) bonds (Scheme 3) as well as thermochemical and equilibrium data for the exchange reactions shown in Scheme 4. As a comparison standard for the exchange process of Scheme 4, we choose R^1 = ma.

Geometry and Conformation. The starting geometry for the simplest molecules was constructed in a straightforward manner. More complex molecules, such as *dmam*S_2CMe for instance, present a conformational problem. We used knowledge from our previous study[23] in order to obtain the most stable conformation in those cases. In particular, we found that there is an energetic preference for the carboxylate unit $C^1−C(O)−O−C^2$ to adopt a planar configuration with a 180° dihedral angle

(a) Dithioacetates



(b) Dithiobenzoates

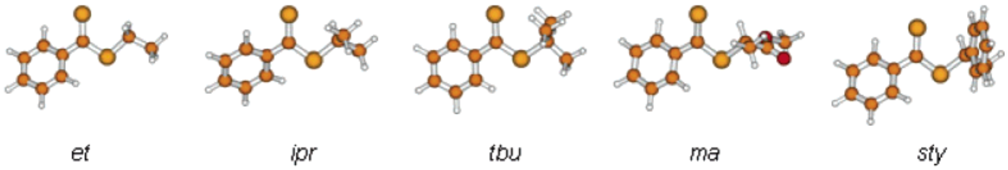


Figure 1. Views of the optimized geometries for all R−SC(S)Z (Z = Me, Ph) molecules.

(i.e., C^2 is located syn to the carbonyl oxygen atom rather than anti). Relative to the simpler R−X molecules where X = halogen (single atom), two new conformational degrees of freedom are introduced for most R radicals by the dithioacetate unit, namely, the two dihedral angles Z−C(S)−S−R and C(S)−S−C−X (Z = CH_3 or C_6H_5; X = any pivot substituent, e.g., the Ph group for *bz* and *sty*, or the Me group for *vf*, *vcl*, *vbr*, *an*, etc.). By running a few comparison calculations, the first dihedral angle was found to favor the disposition of the R group syn with respect to the thiocarbonyl sulfur atom, just like for the normal carboxylic unit (the energy difference is systematically in the 4−5 kcal mol^{-1} range). These conformations correspond to those reported by Coote for the $CH_3SC(S)Z$ compounds with Z = CH_3, Ph, and CH_2Ph.[25] The only one exception to this rule is the *tos* group, which leads to a lower energy geometry (by 4.2 kcal mol^{-1}) when located in the anti position. The C(S)−S−C−X dihedral angle is found to favor conformations having the smaller X substituents closer to the thiocarbonyl group, although the energy difference in this case is smaller (e.g., 0.28 kcal mol^{-1} for *vf*S_2CMe and 0.78 kcal mol^{-1} for *ma*S_2CMe). Comparative views of all optimized dithioacetates are shown in Figure 1a.

The starting geometry for the dithiobenzoates was constructed from the corresponding optimized dithioacetate. The optimized geometries of these systems are shown in Figure 1b. The same essential conformational features of the related dithioacetate systems are found for this series. The dithiobenzoate phenyl ring prefers a slightly tilted conformation relative to the C−C(S)−S plane (ca. 30°), presumably because of a van der Waals interaction between the ring *o*-H atoms and the two S atoms.

Table 1. Calculated $\Delta H°$, $\Delta S°$, and $\Delta G°$ for the $R-S_2CZ$ Bond Breaking Process at 298 K[a]

R	Z	$\Delta H°_{298}$/ kcal mol^{-1}	$\Delta S°_{298}$/ cal K^{-1} mol^{-1}	$\Delta G°_{298}$/ kcal mol^{-1}
et	Me	62.69	49.98	47.78
	Ph	60.21	46.65	46.30
ipr	Me	59.44	49.68	44.63
	Ph	57.19	50.20	42.23
vf	Me	58.76	46.15	45.00
ve	Me	57.53	51.07	42.31
vbr	Me	57.10	47.73	42.87
voac	Me	55.69	47.53	41.52
vcl	Me	54.84	47.72	40.61
vdf	Me	54.03	51.14	38.79
tbu	Me	53.88	57.00	36.89
	Ph	50.47	57.76	33.25
dmam	Me	52.40	49.00	37.79
vk	Me	51.24	51.10	36.00
dcm	Me	50.25	45.58	36.66
bz	Me	49.80	40.83	37.63
ma	Me	49.55	42.42	36.90
	Ph	47.37	43.71	34.34
an	Me	46.58	46.87	32.61
sty	Me	46.37	46.30	32.57
	Ph	44.28	46.25	30.49
vdcl	Me	44.29	49.50	29.53
all	Me	43.29	49.69	28.48
mma	Me	41.07	50.30	26.07
tcm	Me	39.57	52.32	23.97
tos	Me	29.67	46.81	15.71

[a] The necessary thermochemical parameters for the free R radicals were taken from the previous study.[23]

Thermochemistry. The computed thermochemical data for the homolytic rupture of the $R-S_2CZ$ bonds are presented in Table 1. The values are shown in a decreasing order of bond dissociation enthalpy, i.e., BDE at 298 K, for the dithioacetate series. The BDEs show the same general trend previously reported for the other R−X series, the simple alkyl and halogenated alkyl radicals giving the stronger bonds and the more stabilized radicals (*sty*, *all*, *mma*, etc.) the weaker bonds. Comparing the current results with those obtained for

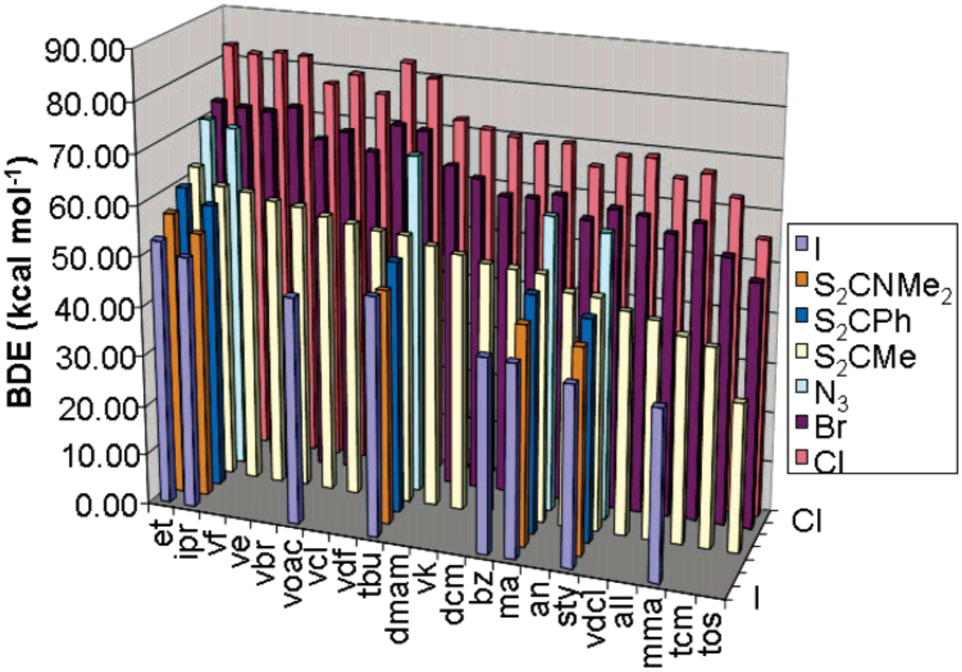


Figure 2. Graphical representation of the R−X BDEs ($\Delta H°_{298}$) as a function of R and X. The chosen order of R is that giving a monotonic decreasing BDE order for the dithioacetate series.

Table 2. Calculated $\Delta\Delta G°$ Values at 298 K for the Exchange Reaction *ma*-X + $R^{\bullet} \rightleftarrows$ $ma^{\bullet}$ + R−X[a]

R	X I	 S_2CNMe_2	 S_2CPh	 S_2CMe	 N_3	 Br	 Cl
et	−14.28	−12.50	−11.97	−10.88	−11.77	−11.38	−12.66
ipr	−10.84	−7.17	−7.89	−7.72	−9.71	−9.85	−10.73
vf				−8.10		−10.28	−12.20
ve				−5.41		−11.35	−11.65
vbr				−5.97		−5.61	−6.63
voac	−6.32			−4.62		−7.68	−8.99
vcl				−3.71		−4.08	−5.45
vdf				−1.89		−10.09	−12.42
tbu	−7.39	−0.94	1.08	0.01	−7.36	−8.25	−8.52
dmam				−0.89		−2.31	−1.73
vk				0.90		−1.49	−0.91
dcm				0.24		1.36	0.53
bz	−1.24			−0.73		−0.39	−0.42
ma	0.00	0.00	0.00	0.00	0.00	0.00	0.00
an				4.30		4.65	4.61
sty	2.62	2.85	3.84	4.33	2.00	1.58	1.65
vdcl				7.37		2.83	1.82
all				8.42		4.92	4.59
mma	4.57			10.83		2.41	3.01
tcm				12.93		8.57	8.29
tos				21.19		12.23	14.75

[a] Values are given in kcal mol^{-1}. The values relative to X = Cl, Br, I, N_3, and S_2CNMe_2 were calculated from previously published data.[23]

the other R−X series, we observe that a given R forms a stronger bond in the order I < S_2CNMe_2 < S_2CPh < S_2CMe < N_3 < Br < Cl, as can be visually appreciated from Figure 2. It can be noted, however, that there are many inversions of relative BDE ordering when going from the dithioacetate series to the Br and Cl series. For instance, *vdf* gives a much stronger bond than *vcl* with Cl and Br, whereas it forms a slightly weaker bond with S_2CMe. Another interesting case is *an*, which forms a weaker bond with Cl and Br relative to *sty* and *vdcl*, whereas the reverse is true for the bond with dithioacetate.

This variation in relative bond energy ordering can be even better appreciated by comparing the exchange free energies, $\Delta\Delta G°$ [expressed relative to the standard *ma* radical: $\Delta\Delta G°(R) = \Delta G°(ma) - \Delta G°(R)$] for the dithioacetate series (Scheme 4), with the corresponding values obtained from the BDE's of other R−X systems. These data are explicitly shown in Table 2. The trends shown by the Cl and Br series agree quite well with each other but are rather different than those of the dithioacetate and dithiobenzoate series. The latter ones agree better with the few examples calculated for the dithiocarbamate series (cf. for instance the values of *tbu*).

The different value of $\Delta\Delta G°$ for some of the systems can be clearly attributed to steric effects. For a larger X group, a larger R (relative to the standard *ma*) will tend to give less negative (or more positive) enthalpy values for the exchange process. This explains rather well the *tbu* trend. Note that the effect is shown also within the halide series but becomes particularly important on going to the more sterically demanding dithioacetate and especially dithiobenzoate and dithiocarbamate. A similar trend is shown by *mma*. Smaller R groups (relative to *ma*) show the opposite trend (e.g., see the *et* series on going from Cl to I). However, an electronic effect superimposes with the steric effect. This is most clearly shown by the large differences observed for the R groups that bear strongly electronegative substituents on the α-C atom. The $\Delta\Delta G°$ value is less negative for the S_2CMe system relative to the Cl system by 4.1 kcal mol^{-1} for *vf* (one F atom), by 6.25 kcal mol^{-1} for *ve* (one OMe group), by 4.37 kcal mol^{-1} for *voac* (one OAc group), and by 10.53 kcal mol^{-1} for *vdf* (two F atoms). The effect is much smaller but still noticeable for the Cl substituents, i.e., $\Delta\Delta G°$ is essentially the same for the Cl and S_2CMe derivatives of *dcm*, whereas it goes from 8.29 kcal mol^{-1} (Cl) to 12.93 (S_2CMe) for *tcm*, which contains three α-Cl atoms.

Electronic Effects. The electronic effect may be correlated to the ionic contribution to the bond strength. An increase in bond polarity for the R−X bond signifies that some extra energy must be paid to redistribute the charge during the formation of the neutral radical

Table 3. Natural Charge on the C Atom and X Group for All R−X Molecules[a]

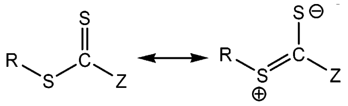
	N_3		Cl		Br		S_2CNMe_2		S_2CPh		S_2CMe		I	
	q(C)	q(X)	q(C)	q(X)	q(C)	q(X)	q(C)	q(X)	q(C)	q(X)	q(C)	q(X)	q(C)	q(X)
bz			−0.458	−0.087	−0.520	−0.039					−0.634	0.062	−0.627	0.048
et	−0.306	−0.207	−0.456	−0.091	−0.520	−0.041	−0.624	0.044	−0.630	0.047	−0.630	0.048	−0.638	0.058
dcm			−0.377	0.028	−0.451	0.083					−0.512	0.167		
vbr			−0.340	−0.020	−0.410	0.032					−0.495	0.136		
an			−0.345	−0.027	−0.406	0.030					−0.513	0.134		
ma	−0.191	−0.172	−0.327	−0.054	−0.386	0.002	−0.501	0.091	−0.503	0.102	−0.507	0.105	−0.501	0.108
vk			−0.323	−0.074	−0.374	−0.012					−0.503	0.098		
dmam			−0.313	−0.073	−0.367	−0.018					−0.488	0.091		
tcm			−0.290	0.072	−0.363	0.129					−0.387	0.189		
vcl			−0.275	−0.031	−0.340	0.020					−0.428	0.126		
all			−0.252	−0.094	−0.304	−0.047					−0.420	0.055		
sty	−0.100	−0.196	−0.234	−0.092	−0.289	−0.043	−0.393	0.052	−0.405	0.063	−0.407	0.065	−0.381	0.032
ipr	−0.094	−0.212	−0.230	−0.101	−0.286	−0.054	−0.396	0.048	−0.400	0.046	−0.402	0.049	−0.390	0.041
vdcl			−0.152	0.025	−0.219	0.078					−0.278	0.163		
mma			−0.110	−0.061	−0.159	−0.008					−0.264	0.080	−0.255	0.088
tbu	0.109	−0.215	−0.016	−0.103	−0.063	−0.060	−0.154	0.036	−0.161	0.036	−0.169	0.047	−0.154	0.028
voac			0.073	−0.087	0.023	−0.045					−0.068	0.053	−0.070	0.033
ve			0.113	−0.157	0.075	−0.134					−0.042	0.005		
vf			0.190	−0.088	0.142	−0.048					0.038	0.060		
vdf			0.744	−0.065	0.702	−0.027					0.633	0.053		
tosa			2.127	−0.272	2.068	−0.212					2.009	−0.070		

[a] Charge for the S atom bonded to X.

species. Therefore, it is logical to expect that an electronegative substituent on the α-C atom renders this atom less negatively (or more positively) charged, thereby decreasing the Coulombic repulsion (or increasing the attraction) with a negatively charged X group. Obviously, the effect is expected to be greater in the order Cl > Br > I and even smaller for the sulfur-based X groups. To test this idea, we have calculated the natural charge[34] on the C atom and on the X group. The results, collected in Table 3, confirm the validity of our hypothesis. To facilitate reading, the table is organized in a different way than the previous ones: the R groups are listed in order of decreasing natural charge for the reference chloride series, whereas the X groups are listed in order of increasing natural charge.

The trends to be noted are as follows: (i) the q(C) charges in the chloride series display the same trend as in the bromide series, which is generally followed also for the dithioacetate series. (ii) q(C) values are slightly negative for those R groups that do not bear O or F substituents on the α-C atom (e.g., in the −0.45 to 0 range for the chloride series). The introduction of O or F substituents increases substantially this charge. The effect is particularly dramatic for *vdf*, having two F substituents on the α-C atom. These trends parallel quite well the discrepancies noted above in Table 2. (iii) Somewhat unexpectedly, the introduction of Br (in *vbr*) or Cl (in *vcl*, *vdcl*, or *tcm*) does not give particularly higher charges for the α-C atom, compared with other groups that do not bear heteroatom substituents. Again, this phenomenon parallels the lack of a particular discrepancy in $\Delta\Delta G°$ for those R groups when going from the Cl and Br series to the dithioacetate series. Thus, an important effect related to the electronegativity difference [both in the q(C) of the α-C atom and in the $\Delta\Delta G°$] seems limited to O and F substituents. (iv) The q(C) charge for a given R group becomes quite expectedly more negative (or less positive) as q(X) becomes less negative. (v) q(X) increases as expected on going from Cl to Br to I; also in line with expectations, it increases, though by a lesser extent, on going from S_2CNEt_2 to S_2CPh and further to S_2CMe; it is in general about the same for I and S_2CMe (slighly more positive with the former for some R groups, with the latter for others). It is necessary to point out that the ionic component of the R−X bond is affected by the resonance contribution of the charge-separated form (see Scheme 5) when X = S_2CMe, S_2CPh, or S_2CNMe_2.[35] (vi) q(X) is quite negative for the azide compounds. This allows us to predict that an anomaly for O- and F-substituted R groups will also occur for the N_3 series, but this time in the opposite direction; namely, $\Delta\Delta G°$ in Table 2 should be more negative for azide compounds relative to the Cl and Br series.

Scheme 5



Scheme 6

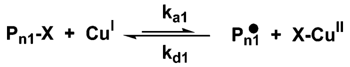
$$P_{n2}^{\bullet} + X\text{-}P_{n1} \xrightleftharpoons{K_{1/2}} P_{n2}\text{-}X + P_{n1}^{\bullet}$$

Similar effects were recently reported for high level ab initio molecular orbital calculations for R = Me, Et, *i*Pr, and *t*Bu and leaving groups with various electronegativity (F, OH, OMe, Me, and H). BDEs depend strongly on the nature of X, and inverse stability orders have been reported and explained by the importance of stabilization of R−X bond by the R^+X^- ionic configuration.[36]

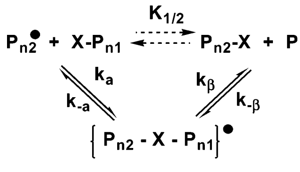
Discussion

The calculated BDE data can be used to estimate the relative values of the equilibrium constants ($K_{1/2}$, see Scheme 6) in CRP. They can be used to compare overall polymerization rates in ATRP but also the relative proportion of dormant and active species exchanging during copolymerization in either ATRP or RAFT. A higher $K_{1/2}$ value indicates relatively higher equilibrium constant K_1 and relatively higher concentration of radicals P_{n1}*. Thus, for higher $K_{1/2}$, more radicals P_{n1}* but also more dormant species P_{n2}−X should be present in comparison with P_{n2}* and P_{n1}−X (see eq 1). The relative stabilities of dormant vs active species for two different alkyl groups can be correlated with the ATRP initiation efficiency, with the chain transfer efficiency

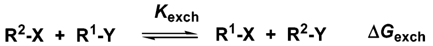
Scheme 7



Scheme 8



Scheme 9



in RAFT, and also with the cross-propagation efficiency in block copolymerization.

$$[P_{n2}-X]/[P_{n1}-X] = K_{1/2}([P_{n2}^*]/[P_{n1}^*]) \tag{1}$$

In ATRP, the $K_{1/2}$ is equal to the ratio $(k_{a1}k_{d2})/(k_{d1}k_{a2})$, where values of k_a and k_d are the activation and deactivation rate constants (see Scheme 7). In RAFT, $K_{1/2}$ formally is equal to the ratio $(k_a k_\beta)/(k_{-a}k_{-\beta})$, where k_a and $k_{-\beta}$ are the rate constants of addition and k_{-a} and k_β are the rate constants of fragmentation (see Scheme 8). The efficiency of cross-propagation in RAFT depends not only on the ratio of the above rate constants but also on their absolute values as well as the rate constants of propagation[5,37] (see eq 2). If fragmentation from the intermediate radical to the initiating/cross-propagating radical P_{n1}^* is slower than to P_{n2}^* ($k_{-a} \gg k_\beta$), then eq 2 reduces to eq 3. Thus, the transfer coefficient for RAFT agents (and also for cross-propagation) should increase with the relative values of $K_{1/2}$. It should also depend on the ratio of the readdition to the cross-propagation rate constant.

$$C_{tr} = \frac{k_a k_\beta}{k_p(k_{-a} + k_\beta)} \tag{2}$$

$$C_{tr} = \frac{k_a k_\beta}{k_p k_{-a}} = \frac{K_{1/2} k_{-\beta}}{k_p} \tag{3}$$

However, it should be noted that the efficiency of RAFT systems depends not only on the overall equilibrium constant $K_{1/2}$ but also on the individual addition and fragmentation rate constants.

Relative Values of Equilibrium Constants. It is interesting to compare not only the equilibrium constants for the radical exchange involving same leaving group X but also the one associated with the double exchange involving two radicals (R^1 and R^2) and two substituents (X and Y) (see Scheme 9). This could aid in a better selection of macroinitiators for block copolymerization and also select better CRP technique for the particular monomers which should be block copolymerized. In ATRP, it is possible to additionally apply halogen exchange to switch successfully from less reactive to more reactive monomers, i.e., polyacrylates to polymethacrylates.[38−41]

Table 4. ΔG_{exch} for the Double Exchange of Scheme 9, Normalized to R^2−Y = Methyl 2-Chloropropionate

	X						
R^1	I	S_2CNMe_2	S_2CPh	S_2CMe	N_3	Br	Cl
et	−1.63	0.16	0.69	1.78	0.88	1.28	0.00
ipr	−0.11	3.56	2.84	3.01	1.03	0.88	0.00
vf				4.10		1.91	0.00
ve				6.25		0.31	0.00
vynbr				0.66		1.01	0.00
voac	2.67			4.37		1.31	0.00
vyncl				1.74		1.37	0.00
vdf				10.54		2.33	0.00
tbu	1.14	7.58	9.60	8.53	1.16	0.27	0.00
dmam				0.83		−0.58	0.00
vk				1.81		−0.57	0.00
dcm				−0.30		0.83	0.00
bz	−0.83			−0.31		0.03	0.00
ma	0.00	0.00	0.00	0.00	0.00	0.00	0.00
an				−0.31		0.04	0.00
sty	0.97	1.20	2.19	2.68	0.35	−0.08	0.00
vdcl				5.55		1.01	0.00
all				3.83		0.33	0.00
mma	1.57			7.83		−0.60	0.00
tcm				4.63		0.27	0.00
tos				6.44		−2.52	0.00

Table 4 presents the computed free energy values for the double exchange of Scheme 9 using methyl 2-X-propionate and Cl as standards for R and X. The reported values are calculated as $\Delta G_{exch}(R^1X) = \Delta\Delta G^X(R^1) - \Delta\Delta G^{Cl}(R^1)$, using the $\Delta\Delta G$ values of Table 2. The $\Delta G_{exch}(R^1X)$ values are relatively small for any R^1 when X = Br, I, and N_3, within the experimental accuracy of DFT (~2 kcal/mol). Slightly larger values were obtained only for *vdf*-Br ($MeCF_2$−Br), *tos*-Br (Me−$PhSO_2$−Br), and *voac*-I (MeC(O)OCH(Me)−I).

However, the ΔG_{exch} values for the dithio compounds are significantly larger for selected R^1 radicals. The largest values are noted for the disubstituted radicals for which K_{exch} is sometimes lower than 10^{-6} [ΔG_{exch} > 10 kcal/mol (*vdf*), ~9 kcal/mol (*tbu*), ~8 kcal/mol (*mma*), and >6 kcal/mol (*tos*)]. It seems that dithioesters and dithiocarbamates of sterically crowded R groups (e.g., *tbu*, *mma*) or groups that are bear very electron-withdrawing substituents in the α position (e.g., *vdf*, *vf*, *ve*, *voac*) transfer the R group to Cl more easily.

These data are in agreement with experimental results. *t*Bu halides are very inefficient ATRP initiators for polymerization of acrylates and other monomers which, on the other hand, are polymerized successfully by ATRP ($\Delta\Delta G°$ ~−8 kcal/mol).[42,43] However, *t*Bu dithioesters perform much better in RAFT $\Delta\Delta G°$ ~ 1 kcal/mol). The relative equilibrium constant is ~10^6 times more favorable (ΔG_{exch} = 9.60 and 8.53 kcal/mol for dithiobenzoate and dithioacetate, respectively) than in ATRP. The relative values of transfer coefficient in RAFT of MMA for various R groups is *mma* > *sty* > *bz* ~ *tbu*.[30,44] This order qualitatively agrees with the order deduced from Tables 2 and 4.

Relative Concentrations of Dormant Species. The $K_{1/2}$ values can also be used to predict relative dormant species concentrations in various statistical copolymerizations. In the fully equilibrated system, the relative proportion of growing radicals is defined by comonomer concentrations and cross-propagation rate constants, which can be estimated from the reactivity ratios and homopropagation rate constants (available, for instance, from pulse laser polymerization experiments) (see eq 4). Combination of this equation with eq 1 leads to eq 5. Thus, a higher concentration of dormant species [P_{n2}−X] will be observed for higher $K_{1/2}$, for higher [M_2], but also for higher r_2 and for lower k_{22}, i.e., when the M_2 monomer propagates slower but cross-propagates slower still.

$$[P_{n2}^*]/[P_{n1}^*] = (k_{12}[M_2])/(k_{21}[M_1]) = (k_{11}r_2[M_2])/(k_{22}r_1[M_1]) \quad (4)$$

$$[P_{n2}-X]/[P_{n1}-X] = K_{1/2}(k_{11}r_2[M_2])/(k_{22}r_1[M_1]) \quad (5)$$

For example, in copolymerization of equimolar amounts of methyl or butyl acrylate with methyl methacrylate at 90 °C ($k_{11} \sim 50\,000$ mol L^{-1} s^{-1}, $k_{22} \sim 2000$ mol L^{-1} s^{-1}, $r_1 \sim 0.3$, $r_2 \sim 3$), the methacrylate radicals will strongly dominate (~250:1), but the concentration of dormant species will depend very strongly on the capping agent. For dithioacetate systems, acrylate dormant chains would strongly dominate over methacrylate dormant species (10^6:1!) although they could be comparable for ATRP (Br, Cl).

In copolymerization of equimolar amounts of methyl or butyl acrylate with styrene ($k_{11} \sim 50\,000$ mol L^{-1} s^{-1}, $k_{22} \sim 1000$ mol L^{-1} s^{-1}, $r_1 \sim 0.2$, $r_2 \sim 0.8$), styryl radicals should dominate (200:1). For RAFT mediated by dithioacetates, the concentration ratio of acrylate dormant species to styrene dormant species should be 8:1, for dithiobenzoates this ratio should be 3:1, but for dithiocarbamate, bromide and chloride a reverse ratio should be observed (~1:2, 1:14, and 1:12, respectively). Indeed, it would be interesting to compare the relative proportion of dormant species in real CRP systems with those predicted by these calculations.

Conclusions

DFT was used to calculate bond dissociation energies for dormant species relevant to RAFT process and compared to those relevant for ATRP. The BDEs, free energies of dissociation and derived equilibrium constants scale in a similar way for both RAFT and ATRP processes, but there are also significant differences which have their origin in polar effects as well as in steric effects. Thus, tertiary dithioesters cleave relatively easier than the corresponding halides. This correlates well with much better initiation efficiency for *t*Bu dithioesters in RAFT than *t*Bu halides in ATRP. The relative values of equilibrium constants can be also used to estimate ratios of concentrations of dormant species in copolymerization of various comonomers in several CRP systems. For example, in conventional radical copolymerization of styrene and methyl acrylate, styryl radicals should strongly dominate (200:1). However, for RAFT mediated by dithioacetates, the concentration ratio of acrylate dormant species to styrene dormant species should be 8:1, for dithiobenzoates this ratio should be 3:1, but for bromide and chloride a ratio 1:14 and 1:12 should be observed, respectively.

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