

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/215675438>

# Thiocarbonylthio Compounds (SC(Z)S–R) in Free Radical Polymerization with Reversible Addition–Fragmentation Chain Transfer (RAFT Polymerization). Effect of the Activating Group Z

ARTICLE in *MACROMOLECULES* · APRIL 2003

Impact Factor: 5.8 · DOI: 10.1021/ma020883+

CITATIONS

426

READS

420

8 AUTHORS, INCLUDING:



**John Chiefari**

The Commonwealth Scientific and Industrial ...

51 PUBLICATIONS 5,450 CITATIONS

SEE PROFILE



**Roshan Mayadunne**

The Commonwealth Scientific and Industrial ...

39 PUBLICATIONS 6,051 CITATIONS

SEE PROFILE



**Graeme Moad**

The Commonwealth Scientific and Industrial ...

221 PUBLICATIONS 16,239 CITATIONS

SEE PROFILE



**Almar Postma**

The Commonwealth Scientific and Industrial ...

74 PUBLICATIONS 4,014 CITATIONS

SEE PROFILE

# Thiocarbonylthio Compounds ( $S=C(Z)S-R$ ) in Free Radical Polymerization with Reversible Addition-Fragmentation Chain Transfer (RAFT Polymerization). Effect of the Activating Group Z

John Chiefari, Roshan T. A. Mayadunne, Catherine L. Moad, Graeme Moad,\*  
Ezio Rizzardo,\* Almar Postma, Melissa A. Skidmore, and San H. Thang\*

CSIRO Molecular Science, Bag 10, Clayton South, Victoria 3169, Australia

Received June 7, 2002; Revised Manuscript Received December 16, 2002

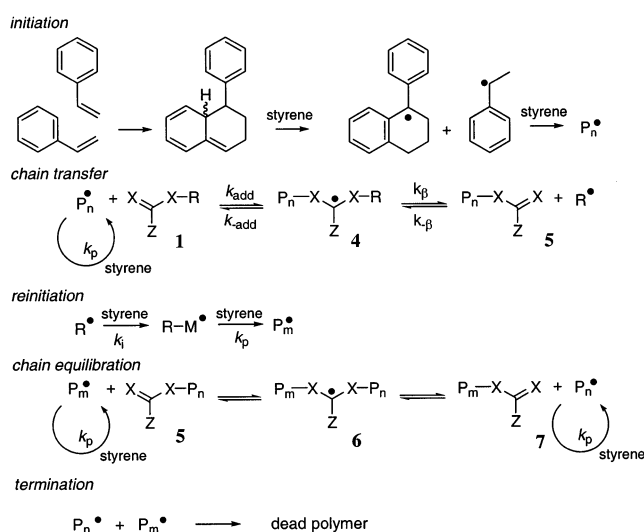
**ABSTRACT:** Free-radical polymerization in the presence of suitable addition–fragmentation chain transfer agents [ $S=C(Z)S-R$ ] (RAFT agents) possess the characteristics of a living polymerization (i.e., polymer products can be reactivated for chain extension and/or block synthesis, molecular weights are predetermined by RAFT agent concentration and conversion, narrow polydispersities are possible). Styrene polymerizations (110 °C, thermal initiation) were performed for two series of RAFT agents [ $S=C(Z)S-CH_2Ph$  and  $S=C(Z)S-C(Me)_2CN$ ]. The chain transfer coefficients decrease in the series where Z is  $Ph > SCH_2Ph \sim SMe \sim Me \sim N$ -pyrrolo  $\gg OC_6F_5 > N$ -lactam  $> OC_6H_5 > O(alkyl) \gg N(alkyl)_2$  (only the first five in this series provide narrow polydispersity polystyrene ( $< 1.2$ ) in batch polymerization). More generally, chain transfer coefficients decrease in the series dithiobenzoates  $>$  trithiocarbonates  $\sim$  dithioalkanoates  $>$  dithiocarbonates (xanthates)  $>$  dithiocarbamates. However, electron-withdrawing substituents on Z can enhance the activity of RAFT agents to modify the above order. Thus, substituents that render the oxygen or nitrogen lone pair less available for delocalization with the  $C=S$  can substantially enhance the effectiveness of xanthates or dithiocarbamates, respectively. The trend in relative effectiveness of the RAFT agents is rationalized in terms of interaction of Z with the  $C=S$  double bond to activate or deactivate that group toward free radical addition. Molecular orbital calculations and the estimated LUMO energies of the RAFT agents can be used in a qualitative manner to predict the effect of the Z substituent on the activity of RAFT agents.

## Introduction

In recent communications, we have demonstrated that free radical polymerization in the presence of reagents that give reversible addition–fragmentation chain transfer (Scheme 1) can be used to produce narrow polydispersity polymers. These polymers can be chain extended to form block, star, or other polymers of complex architecture.<sup>1–9</sup> The polymerizations (designated RAFT polymerizations) have the characteristics usually associated with living polymerization. However, they appear considerably more versatile than other processes described as “living” or “controlled” free radical polymerization in that they are compatible with a wider range of monomers and reaction conditions. The most effective RAFT agents are certain thiocarbonylthio compounds (1).<sup>3–9</sup>

We<sup>3–10</sup> and others<sup>11–14</sup> have reported that, for polymerization with thiocarbonylthio compounds ( $S=C(Z)S-R$ ), the polydispersity and the degree of molecular weight control obtained under a particular set of reaction conditions depend on the nature of the groups Z and R. R is a homolytic leaving group and the radical  $R^\bullet$  must efficiently reinitiate polymerization to give chain transfer. The influence of the R substituent on the effectiveness of dithiobenzoate derivatives (1, Z = Ph) as RAFT agents is detailed in a companion publication.<sup>15</sup> Z is a group that modifies the reactivity of the thiocarbonylthio compound and of the derived adduct radical. In this paper, we examine the effect of the Z group on the activity of thiocarbonylthio compounds (1)

Scheme 1

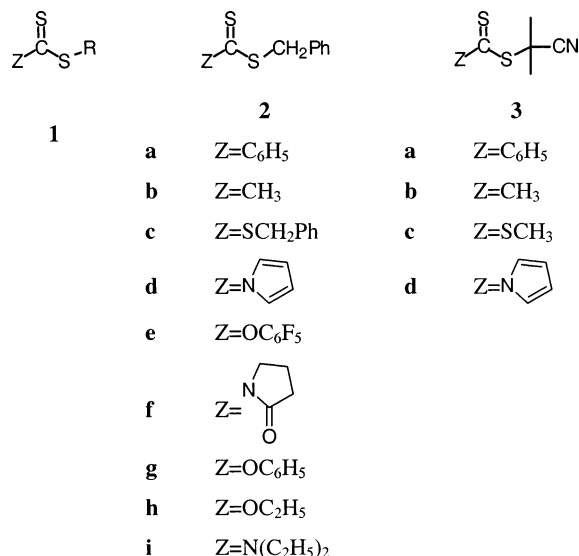


in promoting living polymerization of styrene and draw some general conclusions of the relative effectiveness of various RAFT agents in promoting living radical polymerization.<sup>16</sup>

## Experimental Section

**General Data.** Styrene (Aldrich, 99+%) was purified by filtration through alumina (to remove inhibitors) fractionated under reduced pressure and flash distilled immediately prior to use. Azobis(isobutyronitrile) (AIBN) was obtained from Tokyo Kasei and recrystallized twice from chloroform–methanol. Tetrahydrofuran (THF) used in synthesis was freshly distilled from sodium benzophenone. Solvents used for column chromatography were of AR grade and were distilled.

\* To whom correspondence should be addressed. E-mail addresses: graeme.moad@csiro.au; ezio.rizzardo@csiro.au; san.thang@csiro.au.



Petroleum spirits refers to the fraction with bp 40–60 °C. The silica was Kieselgel-60 (Merck), 70–230 mesh. Reagent chemicals were obtained from Aldrich and were used without further purification unless indicated otherwise. Nuclear magnetic resonance (NMR) spectra were obtained with a Bruker Avance DRX500 or a Bruker AC200 spectrometer on samples dissolved in deuteriochloroform (CDCl<sub>3</sub>). Chemical shifts are reported in ppm from tetramethylsilane. High-resolution chemical ionization mass spectra were obtained with a JEOL JMS DX303 spectrometer with methane as reagent gas. Gel permeation chromatography (GPC) was performed on a Waters Associates liquid chromatograph equipped with differential refractometer and a set of Ultrastaygel columns (10<sup>6</sup>, 10<sup>5</sup>, 10<sup>4</sup>, 10<sup>3</sup>, 500, and 100 Å) at 22 °C. Tetrahydrofuran (flow rate of 1.0 mL/min) was used as eluent. The columns were calibrated with narrow polydispersity polystyrene standards (Polymer Laboratories). Conversions reported in Tables 1–3 were determined gravimetrically.

**Benzyl Dithiobenzoate (2a, Z = Ph).** The preparation of this compound is described elsewhere.<sup>15</sup>

**Dibenzyl Trithiocarbonate (2b, Z = SCH<sub>2</sub>Ph).** The compound was prepared according to the procedure of Leung et al.<sup>17</sup>

**Benzyl Dithioacetate (2c, Z = Me).** Methylmagnesium chloride (10 mL, 0.03 mol, 3M solution in THF, Aldrich) was diluted with THF (10 mL) and the resulting solution warmed to 40 °C. Carbon disulfide (2.28 g, 0.03 mol) was added over 10 min while maintaining the reaction temperature at 40 °C. The reaction was cooled to room temperature before adding benzyl bromide (5.1 g, 0.03 mol) over 15 min. The reaction temperature was increased to 50 °C and maintained for a further 45 min. Water (100 mL) was added and the organic products extracted with *n*-hexane (3 × 60 mL). The combined organic extracts were washed with water and saturated brine and dried over anhydrous magnesium sulfate. After removal of solvent and column chromatography on silica with 5% diethyl ether in *n*-hexane as eluent, pure benzyl dithioacetate was obtained as a golden oil (3 g, 55% yield). <sup>1</sup>H NMR, δ: 2.90 (s, 3H, CH<sub>3</sub>), 4.46 (s, 2H, CH<sub>2</sub>Ph), 7.31 (m, 5H, ArH). Mass spectrum: found 183.0291 (*M* + 1); C<sub>9</sub>H<sub>10</sub>S<sub>2</sub> requires 183.0302.

**Benzyl 1-Pyrrolicarbodithioate (2d, Z = *N*-Pyrrolo).**<sup>18</sup> Pyrrole (1.34 g, 0.02 mol) was added dropwise to a stirred suspension of sodium hydride (0.48 g, 0.02 mol) in dimethyl sulfoxide (20 mL). On completion of addition, the resulting brown solution was stirred at room temperature for 30 min before the addition of carbon disulfide (1.52 g, 0.02 mol). The solution was allowed to stir at room temperature for a further half-hour and benzyl chloride (2.53 g, 0.02 mol) added. Water (20 mL) was added after 1 h, followed by diethyl ether (20 mL). The organic layer was separated and the aqueous layer extracted with diethyl ether (2 × 20 mL). The combined extracts were dried with magnesium sulfate and filtered and

the solvent removed. The crude product was chromatographed on silica eluting with 5% ethyl acetate in petroleum spirits to provide benzyl 1-pyrrolicarbodithioate as a yellow oil (2.34 g, 50% yield). <sup>1</sup>H NMR, δ: 4.60 (s, 2H, CH<sub>2</sub>Ph), 6.30 (m, 2H, pyrrole-*H*3), 7.40 (m, 5H, CH<sub>2</sub>Ph), 7.70 (m, 2H, pyrrole-*H*2). <sup>13</sup>C NMR, δ: 41.7 (CH<sub>2</sub>Ph), 114.2 (pyrrole-*C*3), 120.6 (pyrrole-*C*2), 128.0 (phenyl-*C*2), 128.8 (phenyl-*C*4), 129.4 (phenyl-*C*3), 135.0 (phenyl-*C*1), 189.0 (*C*=S).

**O-Pentafluorophenyl S-Benzyl Xanthate (2e, Z = C<sub>6</sub>F<sub>5</sub>).** Thiophosgene (1.93 g, 0.017 mol) in CHCl<sub>3</sub> (10 mL) at 0 °C was treated dropwise with pentafluorophenol (3.13 g, 0.017 mol) in 5% NaOH (15 mL) cooled to 0–10 °C. The solution was stirred for 1 h at the same temperature, the CHCl<sub>3</sub> layer separated and washed with 5% NaOH (10 mL), 5% HCl (10 mL), and H<sub>2</sub>O (10 mL). The organic layer was dried with MgSO<sub>4</sub> and filtered and the solvent removed to give the perfluorophenyl chlorothioformate (3.76 g).

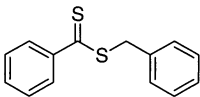
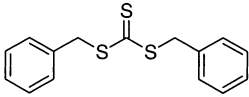
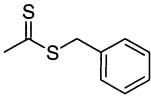
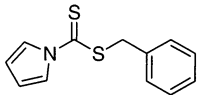
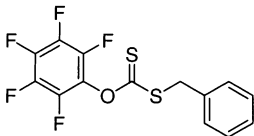
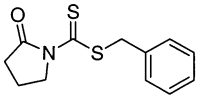
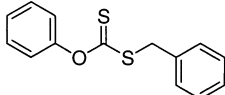
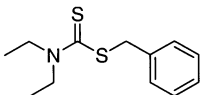
Benzyl mercaptan (1.24 g, 0.01 mol) was added to 0.8 g of NaOH (0.02 mol) dissolved in 20 mL of H<sub>2</sub>O and allowed to stir for 10 min. The crude chlorothioformate (2.63 g, 0.01 mol) was added to the solution and stirred for 2 h. The aqueous solution was extracted with diethyl ether (3 × 30 mL), organic portions were combined, dried with Na<sub>2</sub>SO<sub>4</sub>, and filtered, and the solvent was removed. The residue was purified by chromatography on silica with 2% ethyl acetate in petroleum spirits as the eluent to afford *O*-pentafluorophenyl S-benzyl xanthate (0.89 g, 25% yield). <sup>1</sup>H NMR, δ: 4.5 (s, 2H, CH<sub>2</sub>Ph), 7.3 (m, 5H, ArH). <sup>13</sup>C NMR, δ: 42.9 (CH<sub>2</sub>Ph), 128.3 (phenyl-*C*4), 128.9 (phenyl-*C*2\*), 129.3 (phenyl-*C*3\*), 129.3 (C<sub>6</sub>F<sub>5</sub>-*C*1), 133.9 (phenyl-*C*1), 138.2 (C<sub>6</sub>F<sub>5</sub>-*C*3, J<sub>C-F</sub> 252 Hz), 140.1 (C<sub>6</sub>F<sub>5</sub>-*C*4, J<sub>C-F</sub> 252 Hz), 141.2 (C<sub>6</sub>F<sub>5</sub>-*C*2, J<sub>C-F</sub> 247 Hz), 210.9 (*C*=S) (\* assignments tentative, may be reversed). <sup>19</sup>F NMR (CDCl<sub>3</sub>), δ: -162.5 (m, 2F, *ortho*-F), -156.9 (t, *J* = 22 Hz, 1F, *para*-F), -151.5 (m, 2F, *meta*-F). Mass spectrum: found 350.9917 (*M* + 1); C<sub>14</sub>H<sub>7</sub>S<sub>2</sub>OF<sub>5</sub> requires 350.9937.

**Benzyl 2-Pyrrolidinone-1-carbodithioate (2f).** Benzyl chloride (0.8 g, 0.0064 mol) was added to a suspension solution of 2-pyrrolidinone-1-carbodithioic acid<sup>19</sup> (0.97 g, 0.006 mol) and potassium carbonate (0.84 g, 0.0067 mol) in absolute ethanol (10 mL) at room temperature, and the resulting mixture was stirred at room temperature for 3 h. Water (25 mL) was then added, and the mixture was extracted with ethyl acetate (3 × 20 mL). The combined organic extracts were dried over anhydrous sodium sulfate. The solvent was evaporated under reduced pressure and the residue subjected to column chromatography on silica eluting sequentially with *n*-hexane (to give unreacted benzyl chloride) and with ethyl acetate/*n*-hexane (3:7) to give benzyl 2-pyrrolidinone-1-carbodithioate (1.1 g, 73% yield) as a bright yellow solid, mp 57–58 °C. <sup>1</sup>H NMR, δ: 2.11 (ddt, 2H, -CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>-), 2.73 (t, 2H, -CH<sub>2</sub>C(=O)-), 4.25 (dd, 2H, -CH<sub>2</sub>-N<), 4.40 (s, 2H, CH<sub>2</sub>Ph), 7.20–7.40 (m, 5H, ArH). Mass spectrum: found 252.0510 (*M* + 1); C<sub>12</sub>H<sub>13</sub>S<sub>2</sub>ON requires 252.0517.

**O-Phenyl S-Benzyl Xanthate (2g, Z = Ph).**<sup>20</sup> Benzyl mercaptan (1.24 g, 0.01 mol) was added to an aqueous (20 mL) solution of NaOH (0.8 g) at room temperature and stirred for 15 min. Phenyl thionochloroformate (2.07 g, 0.012 mol) was next added dropwise to this solution at the same temperature and stirred for a further 2 h. Diethyl ether (20 mL) and water (50 mL) were added and the organic layer separated. The aqueous layer was extracted with diethyl ether (3 × 20 mL). The combined organic fractions were dried with Na<sub>2</sub>SO<sub>4</sub> and filtered, the solvent was removed under vacuum, and the crude product was chromatographed on silica with 2% ethyl acetate in petroleum spirits as eluent to afford *O*-phenyl S-benzyl xanthate (1.95 g, 75% yield) as a yellow oil. <sup>1</sup>H NMR, δ: 4.43 (s, 2H, CH<sub>2</sub>Ph), 7.10–7.50 (m, 10H, ArH). <sup>13</sup>C NMR, δ: 41.7 (CH<sub>2</sub>Ph), 122.1 (phenoxy-*C*2), 126.7 (phenoxy-*C*4), 127.8 (phenyl-*C*2), 128.8 (phenyl-*C*4), 129.3 (phenoxy-*C*3), 129.6 (phenyl-*C*3), 135.1 (phenyl-*C*1), 154.0 (phenoxy-*C*1), 213.0 (*C*=S).

***N,N*-Diethyl S-Benzyl Dithiocarbamate (2i, Z = NMe<sub>2</sub>).** A 100 mL, three-neck round-bottom flask was equipped with magnetic stirrer, condenser, and dropping funnel. Sodium *N,N*-diethyldithiocarbamate trihydrate (8.20 g, 0.036 mol) was dissolved in ethanol (40 mL, 99%) and added to the reaction

**Table 1. Molecular Weights and Polydispersities Obtained in Thermal Polymerizations of Styrene with Benzyl RAFT Agents (2) at 110 °C**

RAFT Agent (2)	Time (h)	[2] (10 <sup>-2</sup> M)	$\overline{M}_n$	$\overline{M}_w / \overline{M}_n$	%Conv.
Control	1	0	361000	1.81	5.3
	16	0	324000	1.74	72
	1	2.912	2100	1.27	4.8
	4		5300	1.16	19
	16		15800	1.11	53
	1	2.917	2300	1.54	4.7
	4		6000	1.41	21
	16		17200	1.19	65
	1	2.944	3900	1.64	4.9
	4		6700	1.43	18
	16		17300	1.20	65
	1	2.941	4600	1.79	5.2
	4		7900	1.50	18
	16		18600	1.24	62
	1	2.944	14200	1.70	6.4
	4		16600	1.74	20
	16		23000	1.62	66
	1	2.944	12700	2.15	6.0
	4		20000	1.79	24
	1	2.921	22900	1.91	6.0
	4		32200	1.83	22
	16		37500	1.76	61
	1 (80 °C) <sup>a</sup>	0	58900	1.58	<10
	1 (80 °C) <sup>a</sup>	226.4	57400	1.60	<10
	1 (80 °C) <sup>a</sup>	514.8	48300	1.76	<10
	1 (80 °C) <sup>a</sup>	1043.9	37600	1.85	<10
	1 (120 °C) <sup>b</sup>	0	163000	1.82	<30
	1 (120 °C) <sup>b</sup>	26.22	127000	1.85	<30
	1 (120 °C) <sup>b</sup>	50.69	105000	1.80	<30
	1 (120 °C) <sup>b</sup>	97.53	79400	1.81	<30

<sup>a</sup> AIBN initiator, 80 °C. <sup>b</sup> Di-*tert*-butyl peroxide initiator, 120 °C.

flask under a nitrogen atmosphere at 0 °C. A solution of benzyl chloride (5.10 g, 0.041 mol) in ethanol (10 mL) was added dropwise over 30 min. The reaction was gradually warmed to room temperature, and stirring was continued for a further 65 h. The precipitate (sodium chloride) was filtered off and the filtrate concentrated under vacuum. Vacuum distillation gave 6.18 g (64.5% yield) of a pale yellow liquid, bp 154–156 °C (0.5 mmHg) (lit.<sup>21</sup> bp 154–155 °C (1 mmHg)). <sup>1</sup>H NMR,  $\delta$ : 1.3 (t, 6H, NCH<sub>2</sub>–CH<sub>3</sub>), 3.7 (q 2H, NCH<sub>2</sub>–CH<sub>3</sub>), 4.05 (q, 2H,

NCH<sub>2</sub>–CH<sub>3</sub>), 4.57 (s, 2H, SCH<sub>2</sub>Ph), 7.2–7.5 (m, 5H, ArH).

**2-Cyanoprop-2-yl Dithiobenzoate (3a, Z = Ph).** The preparation of this compound is described elsewhere.<sup>15</sup>

**S-Cyanoprop-2-yl S'-Methyl Trithiocarbonate (3b, Z = SMe).** A solution of bis((methylthio)thiocarbonyl)disulfide<sup>22</sup> (1.23 g, 0.005 mol) and AIBN (1.25 g, 0.0076 mol) in benzene (10 mL) was degassed with a stream of nitrogen and heated under reflux for 24 h. The solvent was removed under vacuum and the residue chromatographed on silica with 20% ethyl



acetate in petroleum spirits as eluent to afford *S*-cyanoprop-2-yl *S*-methyl trithiocarbonate (0.09 g, 47% yield).  $^1\text{H}$  NMR,  $\delta$ : 1.85 (s, 6H,  $2 \times \text{CH}_3$ ), 2.75 (s, 3H,  $\text{SCH}_3$ ).  $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ ),  $\delta$ : 19.1 ( $\text{SCH}_3$ ), 27.0 ( $2 \times \text{CH}_3$ ), 43.0 ( $\text{C}(\text{CH}_3)_2\text{CN}$ ), 120.0 (CN), 199.0 ( $\text{C}=\text{S}$ ). Mass spectrum: found 191.9989 ( $M + 1$ );  $\text{C}_6\text{H}_9\text{S}_3\text{N}$  requires 191.9976.

**2-Cyanoprop-2-yl Dithioacetate (3c, Z =  $\text{CH}_3$ ).** Methylmagnesium chloride (20 mL, 0.06 mol, 3M solution in THF, Aldrich) was diluted with THF (10 mL) and warmed to 40 °C, and carbon disulfide (4.56 g, 0.06 mol) was added dropwise over 15 min while maintaining the reaction temperature at 40 °C. After 1 h, the mixture was allowed to cool to room temperature and then poured slowly into ice water (100 mL) and extracted with diethyl ether (50 mL). The aqueous layer was acidified to pH 2 with cold hydrochloric acid (10% aqueous solution) and extracted with diethyl ether ( $2 \times 50$  mL). The organic extracts were combined, dried over anhydrous magnesium sulfate, and filtered, and the solvent was evaporated to leave dithioacetic acid (5.2 g, 94% yield) as a dark yellow oil. Dithioacetic acid is unstable and was used immediately as follows.

A mixture of dithioacetic acid (5.2 g, 0.056 mol) and  $\alpha$ -methylstyrene (10 mL) were heated under nitrogen at 70 °C for 72 h. The excess  $\alpha$ -methylstyrene was removed under vacuum and the residue chromatographed on silica with 3% ethyl acetate in petroleum spirits as eluent to afford 2-phenylprop-2-yl dithioacetate<sup>23</sup> (4.5 g, 45% yield) as a yellow oil.  $^1\text{H}$  NMR,  $\delta$ : 1.90 (s, 6H,  $2 \times \text{CH}_3$ ), 2.70 (s, 3H,  $\text{CH}_3$ ), 7.20–7.25 (m, 3H, *meta*, *para*-ArH), 7.45 (d, 2H, *ortho*-ArH).  $^{13}\text{C}$  NMR,  $\delta$ : 27.9 ( $2 \times \text{CH}_3$ ), 40.6 ( $\text{CH}_3$ ), 56.1 ( $\text{C}(\text{CH}_3)_2\text{Ph}$ ), 126.6 (phenyl-*C2*), 126.8 (phenyl-*C4*), 128.1 (phenyl-*C3*), 144.5 (phenyl-*C1*).

A solution of 2-phenylprop-2-yl dithioacetate (1 g) and AIBN (1.17 g) in benzene (10 mL) was degassed and heated in vacuo at 80 °C for 18 h. The solvent was removed under vacuum to provide a residue (1.99 g) which was chromatographed on silica with 6% ethyl acetate in petroleum spirits as eluent to afford 2-cyanoprop-2-yl dithioacetate (380 mg, 50%) as a yellow oil.  $^1\text{H}$  NMR ( $\text{CDCl}_3$ ),  $\delta$ : 1.82 (s, 6H,  $2 \times \text{CH}_3$ ), 2.77 (s, 3H,  $\text{CH}_3$ ).

Cyanoisopropyl dithioacetate is unstable and decomposes over several days at –20 °C.

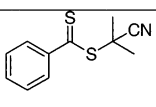
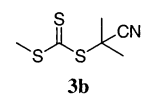
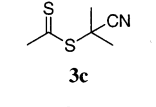
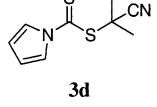
**2-Cyanoprop-2-yl 1-Pyrrolicarbodithioate (3d, Z = Pyrrole).** A solution of pyrrole *N*-thiocarbonyl disulfide (0.15 g)<sup>24</sup> and AIBN (0.16 g) in ethyl acetate (5 mL) was degassed and heated in vacuo at 70 °C for 24 h. The solvent was removed under vacuum and the residue chromatographed on silica with 10% ethyl acetate in petroleum spirits as eluent to afford 2-cyanoprop-2-yl 1-pyrrolicarbodithioate (135 mg, 61% yield).  $^1\text{H}$  NMR,  $\delta$ : 1.99 (s, 6H,  $2 \times \text{CH}_3$ ), 6.38 (m, 2H, pyrrole-*H3*), 7.61 (m, 2H, pyrrole-*H2*).  $^{13}\text{C}$  NMR,  $\delta$ : 27.0 ( $2 \times \text{CH}_3$ ), 44.0 ( $\text{C}(\text{CH}_3)_2\text{CN}$ ), 114.7 (pyrrole-*C3*), 120.7 [(pyrrole-*C2*) and CN], 193.2 ( $\text{C}=\text{S}$ ). Mass spectrum: found 211.0358 ( $M + 1$ );  $\text{C}_9\text{H}_{10}\text{N}_2\text{S}_2$  requires 211.0364.

**Styrene Polymerizations.** Solutions comprising styrene and the thiocarbonylthio compound were heated at  $110 \pm 1$  °C (polymerization times and exact concentrations are shown in Table 1 or Table 2). The following procedure is typical.

Benzyl dithiobenzoate (35.6 mg) was dissolved in styrene (4.55 g). Aliquots (1 mL; 1 h sample) or (2 mL; 4, 16 h samples) were transferred to ampules which were degassed by four freeze–evacuate–thaw cycles ( $<10^{-4}$  mmHg), sealed, and heated at  $110 \pm 1$  °C for the requisite time in a thermostated oil bath. The ampules were then removed and cooled rapidly. An aliquot (ca. 50 mg) of the reaction mixture was taken for NMR analysis. The excess styrene was removed at ambient temperature under vacuum to leave a residue that was weighed to determine conversion and analyzed by GPC (Table 1).

For NMR the aliquot of reaction mixture (ca. 50 mg) was transferred to an NMR tube and diluted with  $\text{CDCl}_3$  to ca. 500  $\mu\text{L}$ . The residual styrene and benzyl dithiobenzoate was determined by integration of the doublets at  $\delta$  5.3 and 5.8 ppm (styrene  $\text{PhCH}=\text{CH}_2$ ) and the singlet at  $\delta$  4.65 ppm ( $2\text{a PhCH}_2$ ).

**Table 2. Molecular Weights and Polydispersities Obtained in Thermal Polymerizations of Styrene with Various Cyanoisopropyl RAFT Agents (3) at 110 °C**

RAFT agent (3)	Time (hrs.)	[3] ( $10^{-2}$ M)	$\bar{M}_n$	$\bar{M}_w / \bar{M}_n$	%Conv.
 3a	1	2.928	2000	1.09	5.6
	4		6700	1.06	21
	16		18700	1.10	53
 3b	1	2.944	1800	1.24	5.7
	4		6700	1.13	23
	16		18400	1.09	53
 3c	1	2.944	1800	1.37	4.1
	4		6700	1.20	16
	16		22400	1.21	64
 3d	1	2.945	3500	1.19	11.7
	4		10100	1.13	35
	16		20500	1.14	71

The results of these and similar polymerizations are summarized in Tables 1–3.

**Transfer Coefficient of *N,N*-Diethyl *S*-Benzyl Dithiocarbamate (2i).** Stock solutions of AIBN (9.7 mg) in styrene (10 mL) and di-*tert*-butyl peroxide (12.0 mg) in styrene (100 mL) were prepared. *N,N*-Diethyl *S*-benzyl dithiocarbamate (details of amounts used provided in Table 1) was weighed into ampules to which 1 mL of the initiator solution was added. The solutions were degassed by three freeze–evacuate–thaw cycles ( $<10^{-4}$  mmHg), sealed, and heated at  $80 \pm 1$  °C for 45 min (AIBN) or  $120 \pm 1$  °C for 150 min (di-*tert*-butyl peroxide). Conversions were estimated by  $^1\text{H}$  NMR on the reaction mixtures by integration signals of the olefinic protons. Samples were analyzed by GPC to provide the molecular weight data in Table 1.

**Molecular Orbital Calculations.** Semiempirical molecular orbital calculations were performed with MOPAC 6.0 using the Chem3D Ultra package on an Apple Macintosh computer as the graphical user interface. For each compound a complete energy minimization was carried out using the keyword “PRECISE”. For radical species the keyword “UHF” was specified. Multiple conformations were used a starting points for geometry optimization to ensure a global minimum was achieved.

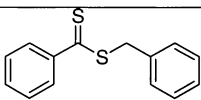
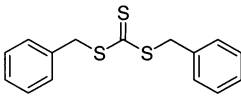
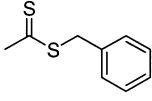
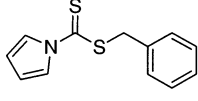
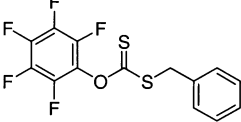
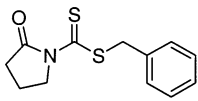
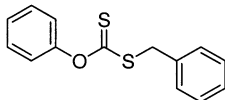
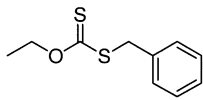
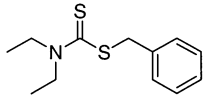
The AM1 Hamiltonian was used for all calculations reported in this paper. Use of the PM3 Hamiltonian was also briefly explored. Trends in LUMO energies for dithiobenzoates were the same. The AM1 was finally selected over the PM3 Hamiltonian as it provides better heat of formation data for free radical species.<sup>25</sup>

All ab initio calculations were performed using the GAUSS-98<sup>26</sup> program on a NEC SX-5 computer. Geometry optimizations were performed using standard gradient techniques at SCF, MP2 and B3LYP levels of theory using RHF for closed shell systems with the basis sets indicated. Vibrational frequencies were calculated for each optimized structure, all structures were confirmed to be ground states. LUMO energies are reported in Figure 8. The Gaussian archive entries for the optimized geometries are provided as Supporting Information.

**Synthesis of Thiocarbonylthio Compounds.** Thiocarbonylthio compounds are available in moderate to excellent yields by a variety of methods. For a summary of the literature, see recent reviews.<sup>27</sup> In the present work, benzyl esters (2) were synthesized by reaction of the appropriate carbodithioate salt with benzyl bromide (Scheme 2).

Cyanoisopropyl esters (3b and 3d) were prepared by the reaction of the corresponding disulfide with cyanoisopropyl radicals generated thermally from AIBN (Scheme 3).<sup>28</sup> Cyanoisopropyl dithioacetate (3c) was prepared by the reaction of cumyl dithioacetate<sup>23</sup> with cyanoisopropyl radicals. We have

**Table 3. Transfer Coefficients for Benzyl RAFT Agents (2) in Thermal Polymerizations of Styrene at 110 °C**

RAFT agent (2)	Time (hrs.)	[2] (10 <sup>-2</sup> M)	%Conv 2 <sup>a</sup> NMR	%Conv 2 <sup>b</sup> MW	%Conv.	C <sub>tr</sub> <sup>c</sup>
 2a	1	2.912	77	72	4.8	29
	4		-	>99	19	(26)
	16		-	>99	53	
 2b	1	2.917	62	59	4.7	18
	4		95	>99	21	(20)
	16		-	>99	65	
 2c	1	2.944	40	38	4.9	10
	4		-	85	18	(9.2)
	16		-	>99	65	
 2d	1	2.941	46	35	5.2	11
	4		82	(75)	18	(7.8)
	16		-	>99	62	
 2e	1	2.944	16	25	6.4	2.3
	4		40	36	20	(2.0)
	16		-	88	66	
 2f	1	2.944	-	15	6.0	(1.6)
	4		-	37	24	
 2g	1	2.921	-	8	6.0	(0.72)
	4		-	21	22	
	16		-	50	60	
 2h						0.105 <sup>d</sup>
 2i						0.009 <sup>e</sup> 0.007 <sup>f</sup>

<sup>a</sup> Evaluated by determination of residual CTA by <sup>1</sup>H NMR (eq 7). <sup>b</sup> Evaluated from the discrepancy between found and calculated molecular weights (eq 8). <sup>c</sup> Transfer coefficient of RAFT agent evaluated from NMR conversions. Value in parentheses comes from molecular weight data by application of eq 8. <sup>d</sup> Literature value at 70 °C,<sup>35</sup> determined by Mayo method. <sup>e</sup> Value at 80 °C, determined by Mayo method with data from Table 1. Literature value<sup>36</sup> at 60 °C is 0.0044. <sup>f</sup> Value at 120 °C, determined by Mayo method with data from Table 1.

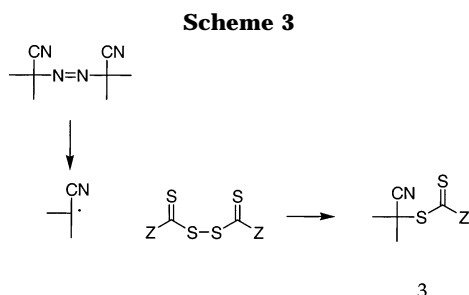
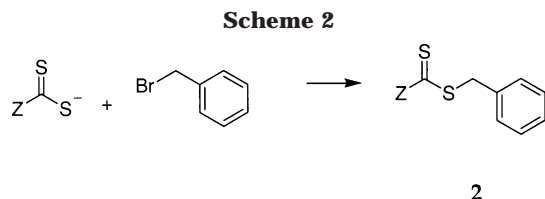
shown elsewhere<sup>15</sup> that cyanoisopropyl dithiobenzoate (**3a**) can also be prepared in high yield by a similar method.

All RAFT agents were purified by column chromatography, crystallization, and/or distillation as appropriate, and the purity was established by NMR analysis and thin-layer chromatography prior to use. Confirmation of identity in the case of novel compounds also came from high-resolution chemical ionization mass spectrometry.

**Styrene Polymerization in the Presence of Thiocarbonylthio Compounds.** To examine the effect of the RAFT

agent Z substituent on RAFT polymerization, styrene polymerizations for RAFT agents **2** (R = benzyl) and **3** (R = 2-cyanoprop-2-yl) were carried out in bulk at 110 °C for various reaction times. All experiments were conducted with ~0.03 M RAFT agent. The results (concentrations, molecular weights, polydispersities, conversions) of these experiments are summarized in Tables 1 and 2, respectively.

The evolution of molecular weight and polydispersity vs conversion for two of the more active RAFT agents, the dithiobenzoate and trithiocarbonate derivatives, are also sum-



marized in Figures 1 and 2. The polydispersity at high conversion is narrow for both benzyl and cyanoisopropyl derivatives.

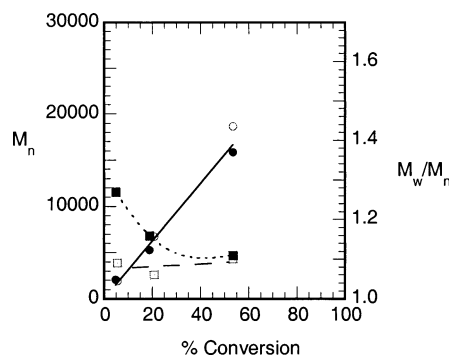
The RAFT agent concentration ( $\sim 0.03$  M) was chosen to be sufficiently high that the proportion of chain ends formed by radical–radical termination would be small and sufficiently low that retardation, which may be pronounced for high concentrations of certain RAFT agents,<sup>9,11,29–32</sup> would also be small. Yields of polymer obtained in the various polymerizations are generally reduced from those obtained in the absence of the RAFT agent but, in general, show no marked dependence on the particular RAFT agent used. The small reduction in yield (e.g. from 72% in the absence of the RAFT agent to ca. 60% with RAFT agent for 16 h reaction time) may be attributed to a lesser gel effect. It is well-established that polymerizations giving lower molecular weight polymers show a reduced gel effect.<sup>33</sup> We have observed that a similar conversion (ca. 60% after 16 h at 110 °C) is obtained in nitroxide-mediated polymerizations initiated by alkoxyamines under these reaction conditions.<sup>34</sup> Slightly lower conversions were observed with the dithiobenzoates **2a** and **3a** (ca. 53% after 16 h) this may be indicative of some retardation (see later discussion); however, the extent is small and not expected to significantly affect the conclusions drawn in this paper. Somewhat higher than anticipated conversions were obtained with **3e** (**1**,  $R = 2$ -cyanoprop-2-yl,  $Z = N$ -pyrrolo). This RAFT agent appears to be thermally unstable and may decompose to form radicals under the polymerization conditions.

**Transfer Coefficients of Thiocarbonylthio Compounds in Styrene Polymerization.** There are few values for the transfer coefficients of thiocarbonylthio compounds (**1**) in styrene polymerization (or other polymerizations) in the literature. Niwa et al.<sup>35</sup> have determined the transfer coefficient of *S*-benzyl-*O*-ethyl dithiocarbonate as 0.105 at 70 °C (this is much lower than that of the corresponding bis-(xanthogen disulfide) 4.44<sup>35</sup>). The transfer coefficient of *S*-benzyl-*N,N*-diethyl dithiocarbamate is reported by Otsu et al.<sup>36</sup> as 0.0044 at 60 °C (that for the corresponding dithiuram disulfide is 0.29<sup>36</sup>). We obtain a similar value at 110 °C (see Table 3).

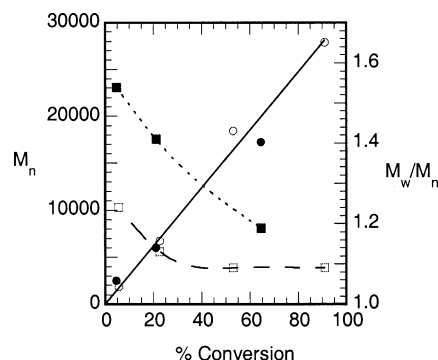
There are also few previous reports on the kinetics of free radical addition to thiocarbonyl compounds<sup>37,38</sup> but little on the substituent effects on the rate constant for addition. It is, nonetheless apparent from this work that the thiocarbonyl double bond ( $C=S$ ) can be very reactive toward free radicals.

In the case of reversible chain transfer, we have shown that the rate of consumption of the transfer agent depends on two transfer constants,  $C_{tr}$  ( $=k_{tr}/k_p$ ) and  $C_{-tr}$  ( $=k_{-tr}/k_i$ ) which describe the reactivity of the propagating radical ( $P_n^\bullet$ ), and the expelled radical ( $R^\bullet$ ) respectively (see eq 1).<sup>39</sup>

$$\frac{d[1]}{d[M]} \approx \frac{k_{tr}[1][P_n^\bullet] - k_{-tr}[5][R^\bullet]}{k_p[M][P_n^\bullet] + k_i[M][R^\bullet]} \quad (1)$$



**Figure 1.** Evolution of polydispersity (■) and molecular weight (●) with conversion for thermal styrene polymerization at 110 °C with benzyl dithiobenzoate (**2a**) (filled symbols) or cyanoisopropyl dithiobenzoate (open symbols). Solid line is calculated molecular weight. Dotted and dashed lines are lines of best fit.



**Figure 2.** Evolution of polydispersity (■) and molecular weight (●) with conversion for thermal styrene polymerization at 110 °C with *S,S*-dibenzyl trithiocarbonate (**2b**) (filled symbols) or *S*-methyl *S*-cyanoisopropyl trithiocarbonate (open symbols). The solid line is calculated molecular weight. Dotted and dashed lines are lines of best fit to the experimental data.

Elimination of the radical concentrations by a steady-state approximation provides eq 2.

$$\frac{d[1]}{d[M]} \approx C_{tr} \frac{[1]}{[M] + C_{tr}[1] + C_{-tr}[5]} \quad (2)$$

This equation can, in principle, be solved numerically to provide estimates of  $C_{tr}$  and  $C_{-tr}$ . If the rate of the reverse reaction between  $R^\bullet$  and the polymeric RAFT agent (**5**) is negligible (low  $C_{-tr}$  and/or low  $[5]$ ), this expression simplifies to an expression (eq 3) that describes conventional chain transfer and the transfer constant can be evaluated from the slope of a plot of  $\ln[1]$  vs  $\ln[M]$ .<sup>40</sup>

$$\frac{d[1]}{d[M]} \approx C_{tr} \frac{[1]}{[M]} \quad (3)$$

$$C_{tr} \approx \frac{d \ln[1]}{d \ln[M]} \quad (4)$$

Values of  $C_{tr}$  reported in this paper have been calculated using eq 4 and should therefore be considered as transfer coefficients for the given reaction conditions rather than transfer constants and be taken as minimum values pending further investigation over a wider range of RAFT agent concentrations.

In chain transfer by addition–fragmentation (refer to Scheme 1), the rate constant for chain transfer ( $k_{tr}$ ) is given by the following expression (eq 5).<sup>41</sup>

$$k_{tr} = k_{add} \times \frac{k_\beta}{k_{-add} + k_\beta} \quad (5)$$

Similarly, the reverse transfer constant ( $k_{-tr}$ ) is given by eq 6.

$$k_{-tr} = k_{-\beta} \frac{k_{-add}}{k_{-add} + k_{\beta}} \quad (6)$$

In this work, the concentration of residual RAFT agent in the reaction mixtures has, where possible, been determined directly by NMR analysis. The  $^1\text{H}$  NMR resonance associated with the benzylic methylene of RAFT agents **2** appears at 4.4–4.6 ppm where there is no interference from other signals. The cyanoisopropyl methyls of **3** appear in the region 1.8–2.0 ppm and may be obscured by signals due to polystyrene.

The signals due to **2** were compared with those due to the residual monomer to give  $([\mathbf{2}]/[\text{M}])_t$ . Then, since the conversion (and  $[\text{M}]_t$ ) is known independently

$$\text{conversion of } \mathbf{2} = ([\mathbf{2}]/[\text{M}])_t [\text{M}]_t / [\mathbf{2}]_0 \quad (7)$$

The concentration of residual RAFT agent can also be calculated from a comparison of found and calculated molecular weights using the following relationship<sup>39</sup>

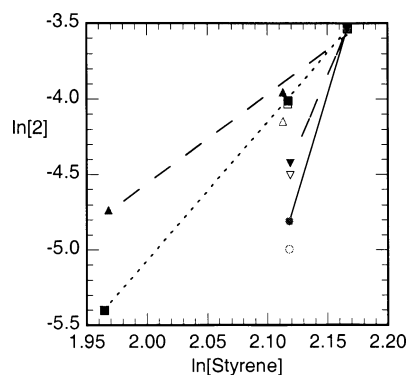
$$\text{conversion of } \mathbf{2} = \frac{[\mathbf{2}]_0 - [\mathbf{2}]_t}{[\mathbf{2}]_0} = \frac{\left\{ \frac{[\text{M}]_0 - [\text{M}]_t}{[\mathbf{2}]_0} \right\} \left\{ \frac{[\text{M}]_0 - [\text{M}]_t}{[\mathbf{2}]_0 - [\mathbf{2}]_t} \right\}}{\left\{ \frac{[\text{M}]_0 - [\text{M}]_t}{[\mathbf{2}]_0 - [\mathbf{2}]_t} \right\}} \approx \frac{\bar{X}_n(\text{calcd})}{\bar{X}_n(\text{found})} \quad (8)$$

where  $\bar{X}_n(\text{calcd})$  is the expected degree of polymerization assuming complete consumption of transfer agent and  $\bar{X}_n(\text{found})$  is the measured degree of polymerization.  $\bar{X}_n(\text{calcd})$  should be corrected for initiator derived chains as discussed elsewhere.<sup>15</sup> For the present polymerization conditions at reaction times  $\leq 4$  h, this correction is small and can be neglected as being within experimental error.

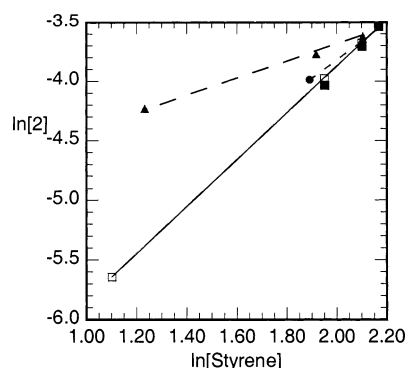
The transfer constants might also, in principle, be estimated from the rate at which the polydispersity or the molecular weight distribution narrows with conversion.<sup>15,31</sup> The polydispersity is more sensitive to changes in  $C_{tr}$  and  $C_{-tr}$  than the number-average molecular weight (see Figures 1 and 2). In other work, we have estimated the value of  $C_{tr}$  and  $C_{-tr}$  for the dithiobenzoate (**2a**) at 60 °C to be  $\sim 400$  and 11600 respectively based on kinetic simulation of the rate of narrowing of the molecular weight distribution (the  $C_{tr}$  (60 °C), calculated from the molecular weight data by assuming  $C_{-tr} = 0$  was 50).<sup>15</sup> This method was not applied in the current work due to insufficient experimental data. It is, nonetheless, evident that  $C_{-tr}$  is significant at 110 °C in that the polydispersities obtained at low conversion are substantially lower than those expected on the basis of the transfer constants shown which assume  $C_{-tr} = 0$ .<sup>15</sup>

Plots of  $\ln[\text{monomer}]$  vs  $\ln[\text{RAFT agent}]$  for the benzyl RAFT agents are shown in Figures 3 and 4. The transfer coefficients of the RAFT agents (**2**, R = benzyl), based on the assumption that eq 4 applies, are reported in Table 3. The value for **2d** seems to reduce with conversion. This may indicate a high  $C_{-tr}$  but may also be due to experimental error. The low conversion  $C_{tr}$  is quoted in Table 3. There is excellent agreement between values obtained using the two methods of estimating residual RAFT agent (i.e., via eqs 7 and 8). Thus, even though the transfer coefficients are based on limited data (two to three data points), they are supported by two independent methods of measurement. The transfer coefficients vary over 4 orders of magnitude (0.01–30), depending on the structure of Z.

The errors in transfer coefficients are difficult to estimate since there is insufficient data for a statistical analysis. Errors are likely to be higher for those RAFT agents having large transfer coefficients. On the basis of the estimated error in determining conversions, in NMR integration and the errors in molecular weight measurement, we estimate the error in the transfer coefficient of **2a** to be  $< 10\%$ . However, since many of the errors are systematic, relative values should be subject to a lesser error.



**Figure 3.** Double log plot of [RAFT agent] vs [styrene] for thermal polymerizations at 110 °C. Residual RAFT agent determined from molecular weight data by application of eq 4 (filled symbols) or from NMR (open symbols). RAFT agent: **2a** (●, —); **2b** (▼, —); **2c** (■, ···); **2d** (▲, ---). Lines are lines of best fit to molecular weight derived data that provide transfer constants shown in Table 3.



**Figure 4.** Double log plot of [RAFT agent] vs [styrene] for thermal polymerizations at 110 °C. Residual RAFT agent determined from molecular weight data by application of eq 4 (filled symbols) or from NMR (open symbols). RAFT agent: **2e** (■, —), **2f** (●, ---), **2g** (▲, ---). Lines are lines of best fit to molecular weight derived data that provide transfer constants shown in Table 3.

For RAFT agents **3** (1, R = 2-cyanoprop-2-yl), the transfer coefficients were too large to be readily measured by the above-mentioned method. The calculated and found molecular weights agree and residual dithioester was not detected by NMR even after short reaction times (at the lowest monomer conversion). A very high transfer constant for 2-cyanoprop-2-yl dithiobenzoate in styrene polymerization is also indicated by the fact that very narrow polydispersities are obtained even at the lowest conversion (see Figure 1 and Table 2). Complete ( $> 95\%$ ) utilization of the initial RAFT agent at 5% conversion suggests  $C_{tr} > 50$ .<sup>15</sup> The actual  $C_{tr}$  may be much higher. With  $C_{-tr} = 0$  it is possible to show that attaining a polydispersity of  $< 1.1$  at 5% conversion requires a  $C_{tr}$  of  $> 500$ .<sup>15</sup>

**Mechanism of RAFT Polymerization.** To understand the effect of the Z group on the effectiveness of the RAFT agent the mechanism of RAFT process must be known. The proposed mechanism for styrene polymerization in the presence of a RAFT agent is shown in Scheme 1.<sup>3</sup> Propagating radicals are generated as in a conventional radical polymerization under the reaction conditions (i.e., thermally from styrene.<sup>42,43</sup> The RAFT agent (**1**) is transformed into a polymeric RAFT agent (**5**) through reaction with a propagating radical ( $P_n\cdot$ ) by an addition–fragmentation process. The radical liberated ( $R\cdot$ ) then reacts with monomer to form a new propagating radical ( $P_m\cdot$ ). Chain extension of the polymeric RAFT agent (**5**) involves essentially the same process. The existence of the radical adducts **4** (and **6**) as intermediates in the addition–fragmentation process has been confirmed by ESR spectrometry.<sup>44</sup> The reversible addition–fragmentation steps transfer the  $\text{S}=\text{C}(\text{Z})\text{S}-$  moiety between active and dormant chains and



provide a mechanism for all chains to grow with similar rate and uniformity. The efficiency of this process determines the living character on the polymerization.

On the basis of the addition–fragmentation mechanism, at least four factors are expected to influence the effectiveness of thiocarbonylthio compounds (**1**): (a) the rate constant of reaction of **1** with the propagating (or initiating) radicals ( $k_{\text{add}}$ ); (b) the partitioning of the adduct (**4**) between starting materials and products (determined by the relative magnitude of ( $k_{-\text{add}}$  and  $k_{\beta}$ ); (c) the absolute rate constant for fragmentation of the intermediate radicals (**4**) ( $k_{\beta}$ ); (d) the rate and efficiency at which the expelled radicals ( $R^{\bullet}$ ) reinitiate polymerization.

Factors a and b should be directly reflected in the magnitude of the transfer coefficient of **1**.

If fragmentation is slow (i.e., both  $k_{-\text{add}}$  and  $k_{\beta}$  are small) or reinitiation of polymerization is slow with respect to propagation, then polymerization may be retarded, and the likelihood of the radicals **4** and/or  $R^{\bullet}$  undergoing side reactions leading to some degree of inhibition is increased. If readdition to reform the adduct radical (**4**) becomes a significant pathway, the situation may arise where the transfer coefficient for chain transfer is dependent on the concentration of the RAFT agent (see above and eq 2).

## Discussion

Within each series of RAFT agent (benzyl (**2**) or cyanoisopropyl (**3**)) the differences in transfer coefficient (Table 3) should mainly reflect the influence of the Z group on the rate of free radical addition to the C=S double bond. The partitioning of the adduct radical (**4**) between starting materials and products should then be determined by the relative leaving group ability of R and the polystyryl radical, and R is constant within each series. The dependence, if any, of the slope of the plots of  $\ln[1]$  vs  $\ln[M]$  on RAFT agent concentration has not been examined and the extent of the back reaction under these conditions is unknown but based on other data is substantial when R is benzyl (see above).<sup>15</sup> The transfer coefficients given in Table 3 should therefore be considered as minimum values. However, the trend in activity within a series (constant R) is not expected to vary from that shown. The transfer coefficients of benzyl dithiobenzoate (**2a**) (ca. 26) and acetate (**2c**) (ca. 10, see Table 3) under our conditions are several orders of magnitude less than the recently reported<sup>10</sup> transfer constant of the corresponding polystyryl derivatives (ca. 6000 and 180 respectively at 60 °C). It is clear that benzyl is a very poor leaving group with respect to the polystyryl radical (i.e.,  $k_{-\text{add}} \gg k_{\beta}$ ). The better leaving group ability of polystyryl vs benzyl is attributed to the influence of steric factors.<sup>15</sup>

Dibenzyl trithiocarbonate (**2b**) possesses two identical leaving groups. Other work<sup>8</sup> shows that both benzyl groups act as leaving groups such that the trithiocarbonate moiety is in the center of the chain. This compound should have a higher transfer coefficient than a monobenzyl compound because there are two pathways for fragmentation from the intermediate adduct.

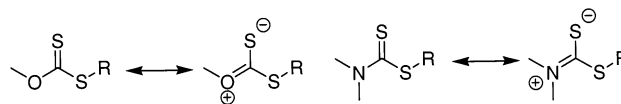
Several factors can be considered to be of importance in determining the rate of free radical addition to thiocarbonylthio compounds. It is clear that product radical stabilities or, rather, the ability of the group Z to stabilize an adjacent radical center is not, by itself, a predictive tool in estimating transfer coefficients. Literature data on C–H bond dissociation energies for compounds ZXYC–H are summarized in Table 4 from which one can infer the relative stabilities of ZXYC• radicals. In attempting to correlate the transfer coefficients of RAFT agents (**2**) with these data, one feature

**Table 4.** C–H Bond Dissociation Energies ( $D_{\text{C–H}}$ ) for Compounds ZXYC–H

Z	$D_{\text{C–H}}$ (kJ mol <sup>−1</sup> ) <sup>a</sup> for X, Y =			
	CH <sub>3</sub> , CH <sub>3</sub> <sup>45</sup>	CH <sub>3</sub> , H <sup>45</sup>	H, H <sup>49</sup>	H, H <sup>50</sup>
H			439	439
CH <sub>3</sub>	400	413		423
(CH <sub>3</sub> ) <sub>3</sub> C			423	
Cl			422	
F			419	
CH <sub>3</sub> S			417	
(CH <sub>3</sub> ) <sub>3</sub> Si			415	
(CH <sub>3</sub> ) <sub>2</sub> P			402	
RO	393 <sup>b</sup>	406 <sup>c</sup>	389 <sup>d</sup>	402 <sup>d</sup>
H <sub>2</sub> N	394	406		391
(CH <sub>3</sub> ) <sub>2</sub> N			352	
CO <sub>2</sub> C <sub>2</sub> H <sub>5</sub>	387	400		
CN	385	397		397
Ph	365	378		375
CH <sub>2</sub> =CH	349	360		367

<sup>a</sup> All numbers rounded to nearest kJ. <sup>b</sup> Z = C<sub>3</sub>H<sub>7</sub>O. <sup>c</sup> Z = C<sub>4</sub>H<sub>9</sub>O. <sup>d</sup> Z = CH<sub>3</sub>O.

**Scheme 4**



which stands out is the relatively low activity of dithiocarbamates (Z = N(alkyl)<sub>2</sub>) and xanthate (Z = O-alkyl) derivatives. These Z substituents might be anticipated to favor addition because of their ability stabilize an adjacent radical center more than (for example) an adjacent aliphatic (Z = alkyl) or sulfur (Z = S-alkyl) substituent (Table 4).<sup>43</sup>

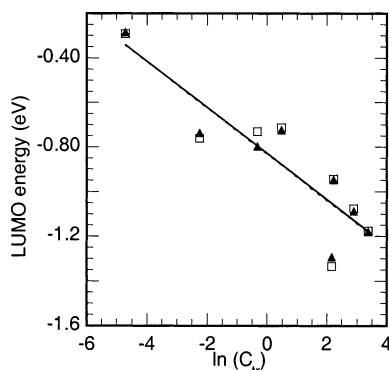
The effect of the Z substituent on the double bond character of C=S should be considered. The relatively low activity of O-alkyl dithiocarbamate and N,N-dialkyl xanthates derivatives can be qualitatively understood in terms of the importance of the zwitterionic canonical forms (see Scheme 4) which arise through interaction between the O or N lone pairs and the C=S double bond. These reduce the C=S double bond character and raise the energy of the LUMO (and HOMO) (see Table 5).<sup>7</sup> These factors should also reduce the reactivity of the C=S double bond of dithiocarbamates and xanthate derivatives toward free radical addition. These same considerations lead to the expectation that substituents that are electron withdrawing or which are able to delocalize the lone pair should enhance the activity of these compounds. Thus, by changing the substituent on nitrogen their activity can be substantially modified such that they become very effective RAFT agents.<sup>6,7,12,46</sup>

The reactions of xanthates with free radicals to give reversible addition–fragmentation and their use in this context as synthetic reagents in organic chemistry has known been for some time.<sup>47</sup> However, prior to the present work,<sup>46</sup> there are little data on what factors affect the rate of radical addition (or of fragmentation from the species formed). We can also note that alkyl xanthates, while comparatively poor RAFT agents in styrene polymerization, are very effective as RAFT agents in vinyl acetate polymerization.<sup>6,46,48</sup> This indicates that the more reactive vinyl acetate propagating radical is able to give facile addition to the xanthate but, more importantly, that fragmentation is also facile. As with dithiocarbamates, the activity of xanthates can be tuned by changing the substituent on oxygen. In styrene polymerization, we find the transfer coefficient increases

**Table 5. HUMO and LUMO Energies, Partial Charges on Sulfur for Thiocarbonylthio Compounds  $ZC(=S)S-CH_3$  (in Order of Decreasing LUMO Energy), and Relative Heats of Reaction for Free Radical Addition of Methyl Radical**

Z	energy (eV)		atomic charge				$\Delta H_r^c$ (kJ mol <sup>-1</sup> )	C=S (Å)
	HOMO	LUMO	=S <sup>a</sup>	-S <sup>a</sup>	=S <sup>b</sup>	-S <sup>b</sup>		
(CH <sub>3</sub> ) <sub>2</sub> N-	-8.59275	-0.29084	-0.171	0.197	-0.222	0.168	41.5	1.59
lactam-	-8.63381	-0.71265	0.029	0.158	-0.065	0.132	72.6	1.56
PhO-	-8.9495	-0.72940	-0.043	0.337	-0.103	0.292	64.1	1.55
CH <sub>3</sub> O-	-9.0183	-0.76045	-0.021	0.312	-0.087	0.317	50.9	1.57
(CH <sub>3</sub> ) <sub>3</sub> Si-	-8.37473	-0.87821	0.072	0.363	0.012	0.329	55.5	1.53
CH <sub>3</sub> -	-8.75059	-0.94518	0.039	0.305	-0.030	0.262	64.5	1.54
CH <sub>3</sub> S-	-8.7506	-1.0759	0.089	0.283	0.002	0.235	66.5	1.55
Ph-	-8.71945	-1.17647	0.032	0.312	-0.037	0.279	70.5	1.55
N-pyrrolo	-8.89483	-1.33411	0.033	0.353	0.035	0.292	74.5	1.57
C <sub>6</sub> F <sub>5</sub> O-	-9.44907	-1.41857	-0.067	0.347	0.000	0.398	78.7	1.55
CCl <sub>3</sub>	-9.1006	-1.6338	0.162	0.403	0.077	0.349	87.5	1.53
CF <sub>3</sub>	-9.3363	-1.7739	0.882	0.426	0.0970	0.368	88.3	1.52

<sup>a</sup> Milliken charge. <sup>b</sup> Atomic charge. <sup>c</sup> Relative heat of reaction =  $\Delta H_f(1) - \Delta H_f(4)$ .

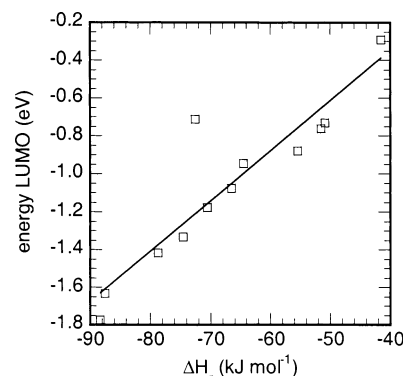
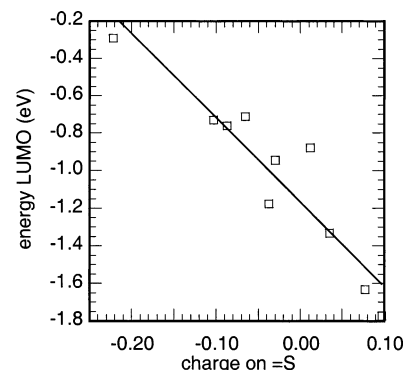
**Figure 5.** Plot of logarithm of transfer coefficient (of  $ZC(=S)S-CH_2Ph$ ) vs calculated LUMO energy for methyl ( $\square$ ,  $ZC(=S)S-CH_3$ , from Table 5) and benzyl ( $\blacktriangle$ ,  $ZC(=S)S-CH_2Ph$ ) RAFT agents.

20-fold over the series  $EtO < C_6H_5O < C_6F_5O$  (see Table 2) as the oxygen lone pair becomes less available for interaction with the C=S double bond.

We have calculated heats of reaction for addition of various radicals to the C=S double bond of thiocarbonylthio compounds using semiempirical molecular orbital methods. Energies of the LUMO and HOMO and atomic charge densities for various thiocarbonylthio compounds have also been calculated. Full geometry optimizations for both the RAFT agent (**1**) and the corresponding adduct (**4**) were performed using the program MOPAC with the AM1 Hamiltonian. Data for various RAFT agents (**1**) with R = methyl are summarized in Table 5. Some calculations were also performed for RAFT agents (**1**) with R = benzyl. While the parameters are dependent on R, the trend in values appears essentially independent of R (Figure 5). The effect of substituents on R on the activity of RAFT agents is discussed elsewhere.<sup>15</sup> There is a good correlation between relative LUMO energies and overall heats of reaction (Figure 6).

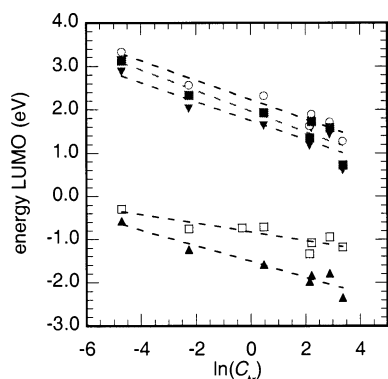
Ab initio methods have also been applied to calculate the properties of the ground states of a series of RAFT agents (**1**), R = methyl. The results validate the trends with LUMO energy seen with the semiempirical calculations. The data are shown in Figure 8. The trends are similar although absolute values differ.

We observe that for dithiocarbamates and xanthates there is a significant charge localized on the thiocarbonyl sulfur (consistent with the above-mentioned hypothesis—Scheme 4) and that this is reduced when the lone pair is able to interact directly with a  $\pi$ -system or an electron-withdrawing group. The correlation of  $\ln(C_{tr})$

**Figure 6.** Correlation of LUMO energy ( $\square$ ,  $\blacktriangle$ ) and relative heat of reaction for methyl radical addition to methyl RAFT agents ( $ZC(=S)S-CH_3$ ). Data come from AM1 calculations. Details are provided in Table 5. The point removed from the line is the system with Z = lactam.**Figure 7.** Correlation of LUMO energy ( $\square$ ,  $\blacktriangle$ ) and charge on =S of methyl RAFT agents ( $ZC(=S)S-CH_3$ ). Data come from AM1 calculations. Details are provided in Table 5.

with the LUMO energy is poorer with these examples included. However, this may reflect the uncertainty in the values of  $C_{tr}$  (see above). There is a reasonable correlation of the LUMO energy with the charge localized on the thiocarbonyl sulfur (Figure 7), which is consistent with a hypothesis that electron-withdrawing Z groups facilitate addition. There appears to be no correlation with C=S bond length or other geometric parameters (Table 5).

One interesting feature of the geometry apparent from both AM1 and ab initio calculations is that the phenyl ring of the dithiobenzoate prefers not to lie coplanar with the C=S double bond. The dihedral angle is 38.4° (AM1) or 35.6° (ab initio) for methyl dithiobenzoate. However, the activation barrier for rotation



**Figure 8.** Plot of logarithm of transfer coefficient (of  $ZC(=S)S-CH_2Ph$ ) vs calculated LUMO energy for methyl RAFT agents ( $ZC(=S)S-CH_3$ ). Values from AM1 calculations ( $\square$ ), ab initio calculations with Gaussian 98 and 3/21G\* ( $\circ$ ), 6/31G\* ( $\blacktriangle$ ) or MP2/D95 ( $\blacktriangledown$ ) basis sets, or density functional calculations with basis set B3LYP/6-31G\* ( $\blacksquare$ ).

through the plane of the C=S bond is very small ( $\sim 0.2$  kJ mol $^{-1}$ ).

Factors which enhance the rate of free radical addition to the C=S double bond of **1** will, in general, also reduce the rate of fragmentation of the adduct **4** (Scheme 1). For efficient chain transfer both addition and fragmentation are required to be facile. A slow overall rate of fragmentation is one possible cause of retardation.<sup>9,31</sup> Rates of polymerization in the present study show no marked dependence on Z and are only slightly reduced for the dithiobenzoates (R=Ph) over those seen with other Z substituents. The retardation with these RAFT agents appears independent of R (the yield after 16 h with **2a** or **3a** is ca. 53% vs ca. 60–65% with most other RAFT agents—Tables 1 and 2). The more severe retardation seen with high concentrations of dithiobenzoate RAFT agents is dependent on R and has therefore been associated with slow fragmentation of the initial adduct (**4**).<sup>9,29</sup> The smaller retardation seen here may be associated with slow fragmentation of the adduct **6**. Other work suggests that slow fragmentation, by itself, is unlikely to be responsible for retardation.<sup>32,44</sup> If, however, fragmentation is slower there is a greater likelihood that side reactions involving **4** and/or **6** such as reversible or irreversible coupling with other radicals will assume greater importance.<sup>11,29,30,32</sup>

## Conclusions

The effect of varying the substituent Z of RAFT agents **1** on the course of RAFT polymerization has been examined. In general, the transfer coefficients of the RAFT agents decreases in the order dithiobenzoates > trithiocarbonates  $\sim$  dithioalkanoates > dithiocarbonates (xanthates) > dithiocarbamates. RAFT agents with electrophilic Z substituents with lone pairs directly conjugated to the C=S double bond (O–, N<) have low transfer coefficients. However, electron-withdrawing groups on O or N (in particular, groups able to delocalize the nitrogen lone pair in the case of dithiocarbamates) can significantly enhance the activity of RAFT agents to modify the above order. The relative effectiveness of the RAFT agents is rationalized in terms of interaction of the Z substituent with the C=S double bond to activate or deactivate that group toward free radical addition. Semiempirical molecular orbital calculations and the estimated LUMO energies or heats of reaction can be used in a qualitative manner to predict relative activity of RAFT agents.

**Acknowledgment.** We are grateful to Drs. C. Berge, M. Fryd, and R. Matheson of DuPont Performance Coatings for their support of this work and for valuable discussion. We thank Ngoc Le for assistance in carrying out the polymerizations with *N,N*-diethyl *S*-benzyl dithiocarbamate.

**Supporting Information Available:** A figure showing the atom numbering for a table giving a summary of the geometry and atomic charges for the thiocarbonylthio group of methyl RAFT agents ( $ZC(=S)S-CH_3$ ) from Gaussian 98 calculations with MP2/D95 basis set and text giving Gaussian archive entries for the optimized geometries with 3/21G\*, 6/31G\*, MP2/D95, and B3LYP/6-31G\* basis sets. This material is available free of charge via the Internet at <http://pubs.acs.org>.

## References and Notes

- Krstina, J.; Moad, G.; Rizzardo, E.; Winzor, C. L.; Berge, C. T.; Fryd, M. *Macromolecules* **1995**, *28*, 5381–5.
- Krstina, J.; Moad, C. L.; Moad, G.; Rizzardo, E.; Berge, C. T.; Fryd, M. *Macromol. Symp.* **1996**, *111*, 13–23.
- Chiefari, J.; Chong, Y. K.; 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*, 5559–62.
- Chong, B. Y. K.; Le, T. P. T.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1999**, *32*, 2071–4.
- Rizzardo, E.; Chiefari, J.; Chong, Y. K.; Ercole, F.; Krstina, J.; Jeffery, J.; Le, T. P. T.; Mayadunne, R. T. A.; Meijs, G. F.; Moad, C. L.; Moad, G.; Thang, S. H. *Macromol. Symp.* **1999**, *143*, 291–307.
- Rizzardo, E.; Chiefari, J.; Mayadunne, R. T. A.; Moad, G.; Thang, S. H. *ACS Symp. Ser.* **2000**, *768*, 278–96.
- Mayadunne, R. T. A.; Rizzardo, E.; Chiefari, J.; Moad, G.; Thang, S. H. *Macromolecules* **1999**, *32*, 6977–80.
- Mayadunne, R. T. A.; Rizzardo, E.; Chiefari, J.; Krstina, J.; Moad, G.; Postma, A.; Thang, S. H. *Macromolecules* **2000**, *33*, 243–5.
- Moad, G.; Chiefari, J.; Krstina, J.; Postma, A.; Mayadunne, R. T. A.; Rizzardo, E.; Thang, S. H. *Polym. Int.* **2000**, *49*, 933–1001.
- Goto, A.; Sato, K.; Tsujii, Y.; Fukuda, T.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **2001**, *34*, 402–8.
- Barner-Kowollik, C.; Quinn, J. F.; Nguyen, T. L. U.; Heuts, J. P. A.; Davis, T. P. *Macromolecules* **2001**, *34*, 7849–57.
- Destarac, M.; Charlot, D.; Franck, X.; Zard, S. Z. *Macromol. Rapid Commun.* **2000**, *21*, 1035–9.
- Ladaviere, C.; Doerr, N.; Claverie, J. P. *Macromolecules* **2001**, *34*, 5370–2.
- Donovan, M. S.; Lowe, A. B.; Sumerlin, B. S.; McCormick, C. L. *Macromolecules* **2002**, *35*, 4123–32.
- Chong, Y. K.; Krstina, J.; Le, T. P. T.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **2003**, *36*, 2256.
- Some results mentioned in this paper have been published previously as part of a conference paper.<sup>9</sup>
- Leung, M.-K.; Hsieh, D.-T.; Lee, K.-H.; Liou, J.-C. *J. Chem. Res. Synop.* **1995**, 478–9.
- Katritzky, A. R.; Lewis, J.; Musumarra, G.; Ogretir, G. *Chim. Acta Turc.* **1976**, *4*, 71–80.
- Takeshima, T.; Ikeda, M.; Yokoyama, M.; Fukada, N.; Muraoka, M. *J. Chem. Soc., Perkin Trans. I* **1979**, 692–5.
- Wakamori, S.; Yoshida, Y.; Tsuchida, T.; Ishii, Y. *Agric. Biol. Chem.* **1969**, *33*, 1691–9.
- Otsu, T.; Kuriyama, A. *Polym. Bull. (Berlin)* **1984**, *11*, 135–42.
- Fuchigami, T.; Chen, C. S.; Nomaka, T.; Yen, M. Y.; Tien, H. *J. Bull. Chem. Soc. Jpn.* **1986**, *59*, 487–91.
- Oae, S.; Yagihara, T.; Okabe, T. *Tetrahedron* **1972**, *28*, 3203–16.
- Oddo, B.; Alberti, C. *Gazz. Chim. Ital.* **1938**, *68*, 204–14.
- Moad, G.; Rizzardo, E. *Macromolecules* **1995**, *28*, 8722–8.
- Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; J. A. Montgomery, J.; 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.; Baboul, A. G.; 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.; J. A. Pople *Gaussian 98 (Revision A.9)*; Gaussian, Inc.: Pittsburgh, PA, 1998.
- (27) Mayer, R.; Scheithauer, S. In *Houben-Weyl Methods of Organic Chemistry*; Buechel, K. H., Falbe, J., Hagemann, H., Hanack, M., Eds.; Thieme: Stuttgart, Germany, 1985; Vol E, pp 891–930.
- (28) Thang, S. H.; Chong, Y. K.; Mayadunne, R. T. A.; Moad, G.; Rizzardo, E. *Tetrahedron Lett.* **1999**, 40, 2435–8.
- (29) Moad, G.; Chiefari, J.; Mayadunne, R. T. A.; Moad, C. L.; Postma, A.; Rizzardo, E.; Thang, S. H. *Macromol. Symp.* **2002**, 182, 65–80.
- (30) Monteiro, M. J.; de Brouwer, H. *Macromolecules* **2001**, 34, 349–52.
- (31) Barner-Kowollik, C.; Quinn, J. F.; Morsley, D. R.; Davis, T. P. *J. Polym. Sci., Part A: Polym. Chem.* **2001**, 39, 1353–65.
- (32) Kwak, Y.; Goto, A.; Tsujii, Y.; Murata, Y.; Komatsu, K.; Fukuda, T. *Macromolecules* **2002**, 35, 3026–9.
- (33) O'Neil, G. A.; Wisnudel, M. B.; Torkelson, J. M. *Macromolecules* **1998**, 31, 4537–45.
- (34) Postma, A.; Moad, G. Unpublished data. For example: A solution of 1-(2-*tert*-butoxy-1-phenylethoxy)-2,5-diethyl-2,5-dimethylimidazolidin-4-one (Chong, Y. K.; Ercole, F.; Moad, G.; Rizzardo, E.; Thang, S. H.; Anderson, A. G. *Macromolecules* **1999**, 32, 6895–903) (12.65 mg) in styrene (0.91 g) was placed in an ampule and degassed through three freeze–evacuate–thaw cycles, and the ampule was sealed and heated at 110 °C for 16 h. The ampule was cooled and opened. The styrene was evaporated under reduced pressure and the residue dried to constant weight. The polystyrene (0.59 g, 65% conversion) was analyzed by GPC and had  $M_n$  16 900,  $M_w/M_n$  1.48.
- (35) Niwa, M.; Matsumoto, T.; Izumi, H. *Makromol. Chem.* **1987**, 189, 2187–99.
- (36) Otsu, T.; Matsunaga, T.; Doi, T.; Matsumoto, A. *Eur. Polym. J.* **1995**, 31, 67–78.
- (37) Alberti, A.; Benaglia, M.; Bonini, B. F.; Pedulli, G. F. *J. Chem. Soc., Faraday Trans. 1* **1988**, 84, 3347–58.
- (38) Scaiano, J. C.; Ingold, K. U. *J. Am. Chem. Soc.* **1976**, 98, 4727–32.
- (39) Moad, C. L.; Moad, G.; Postma, A.; Mayadunne, R. T. A.; Rizzardo, E.; Thang, S. H. *Macromolecules* **2002**, to be submitted.
- (40) Bamford, C. H.; Barb, W. G.; Jenkins, A. D.; Onyon, P. F. *The Kinetics of Vinyl Polymerization by Radical Mechanisms*; Butterworth: London, 1958.
- (41) Moad, G.; Moad, C. L.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1996**, 29, 7717–26.
- (42) Mayo, F. R. *J. Am. Chem. Soc.* **1968**, 90, 1289.
- (43) Chong, Y. K.; Rizzardo, E.; Solomon, D. H. *J. Am. Chem. Soc.* **1983**, 103, 7761–2.
- (44) Hawthorne, D. G.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1999**, 32, 5457–9.
- (45) Brocks, J. J.; Beckhaus, H.-D.; Beckwith, A. L. J.; Rüchardt, C. *J. Org. Chem.* **1998**, 63, 1935–43.
- (46) Chiefari, J.; Mayadunne, R. T. A.; Moad, G.; Rizzardo, E.; Thang, S. H. PCT Int. Appl. WO 99/31144 (*Chem. Abstr.* **1999**, 131, 45250).
- (47) Zard, S. Z. *Angew. Chem., Int. Ed. Engl.* **1997**, 36, 672–85.
- (48) Charmot, D.; Corpart, P.; Adam, H.; Zard, S. Z.; Biadatti, T.; Bouhadir, G. *Macromol. Symp.* **2000**, 150, 23–32.
- (49) Römer, B.; Gatev, G.; Zhong, M.; Brauman, J. L. *J. Am. Chem. Soc.* **1998**, 120, 2919–24.
- (50) Jursic, B. S.; Timberlake, J. W.; Engel, P. S. *Tetrahedron Lett.* **1996**, 37, 6473–4.

MA020883+