Macromolecules **1999,** *32,* 5457−5459

Living Radical Polymerization with Reversible Addition−Fragmentation Chain Transfer (RAFT): Direct ESR Observation of Intermediate Radicals

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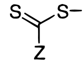
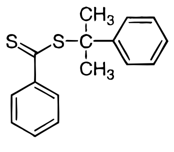
Received March 2, 1999

Living[1] radical polymerization has recently emerged as one of the more effective synthetic routes to well-defined polymers.[2,3] Several approaches have been reported: nitroxide-mediated or alkoxyamine-initiated polymerization[4−6] and atom transfer radical polymerization.[7−10] Most recently, a versatile and robust process based on reversible addition−fragmentation chain transfer (RAFT)[11−14] has been developed in our laboratories.

The RAFT process is accomplished by performing a conventional radical polymerization in the presence of a (thiocarbonyl)sulfanyl compound of general structure S=C(Z)−SR (**1**) (e.g., 2-phenylprop-2-yl dithiobenzoate, **1a**) that acts as an efficient reversible addition−fragmentation chain transfer agent (a RAFT agent) and confers living characteristics onto the polymerization. A major advantage of the RAFT process over other methods for living radical polymerization is its compatibility with a wide range of functional monomers, for example, methacrylic acid, styrenesulfonic acid sodium salt, 2-hydroxyethyl methacrylate, or 2-(dimethylamino)ethyl methacrylate. The products, whether homopolymers, random copolymers, gradient, or block copolymers, are of controlled molecular weight and generally have very narrow polydispersities (usually <1.2, sometimes <1.1).[11−14]



(1)



(**1a**)

It is proposed that the mechanism of the RAFT process (Scheme 1) involves a series of reversible addition−fragmentation steps. Addition of a propagating radical ($P_n^•$) to a (thiocarbonyl)sulfanyl compound S=C(Z)−S−R (**1**) gives an adduct radical (**2**) which can fragment to form polymeric (thiocarbonyl)sulfanyl compound [P_n−S−C(Z)=S] and a new radical $R^•$. The reaction of the radical $R^•$ with a monomer (M) results in a new propagating radical $P_m^•$. Subsequent addition−fragmentation steps allow a dynamic equilibrium to be established between the active propagating radicals ($P_n^•$ and $P_m^•$) and dormant polymeric (thiocarbonyl)sulfanyl compounds [P_n−S−C(Z)=S and P_m−S−C(Z)=S] such that there is an equal probability of growth for all chains, resulting in a narrow molecular weight distribution.

Scheme 1. Proposed Mechanism of the RAFT Process.

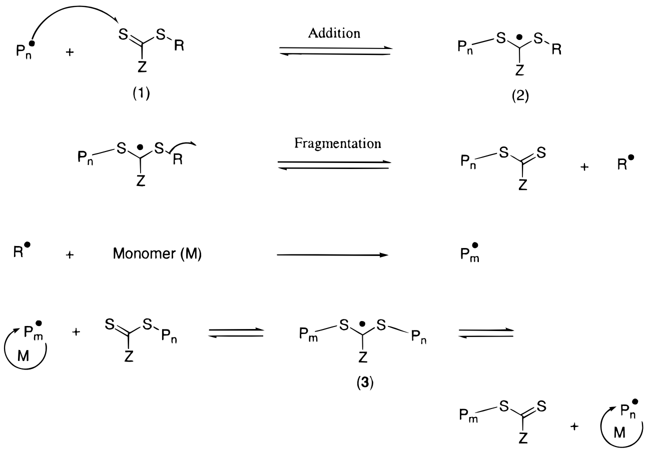
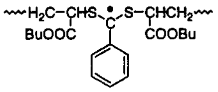
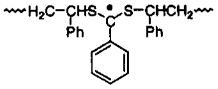
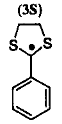
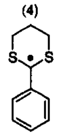
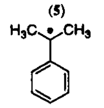


Table 1. ESR Spectral Parameters

radical	hyperfine splittings α_H/G	*g*-factor	reference
 (3A)	3.66 (2H, ortho) 1.41 (2H, meta) 3.96 (1H, para) 0.28 (2H,γ-H)	2.0041	This work
 (3S)		2.0043	This work
 (4)	4.00 (2H, ortho) 1.36 (2H, meta) 4.66 (1H, para) 0.85 (4H, γ-H)	2.0044	22
 (5)	3.82 (2H, ortho) 1.32 (2H, meta) 4.40 (1H, para) 1.32 (4H, γ-H)	2.0046	22
 2-Phenylprop-2-yl	16.00 (6H) 4.70 (2H, ortho) 1.60 (2H, meta) 5.50 (1H, para)	2.0028	20

Evidence for the RAFT mechanism is provided through end group analysis by NMR and UV/visible spectra.[11−13] More recently, a matrix-assisted laser desorption ionization time-of-flight (MALDI-TOF) mass spectrometry analysis has been performed on a narrow polydispersity, low-molecular-weight poly(*N*-isopropylacrylamide)[15] to provide additional support for the proposed mechanism by demonstrating that the S=C(Z)S− and R moieties (from the RAFT agent) are present as the end groups of polymer chains.

However, these results provide no direct information on the reactive intermediates involved in the process (i.e., radicals **2** or **3**; see Scheme 1). It is well-known that electron spin resonance (ESR) spectroscopy is a

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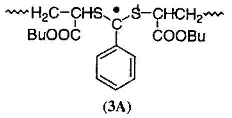


(3A)

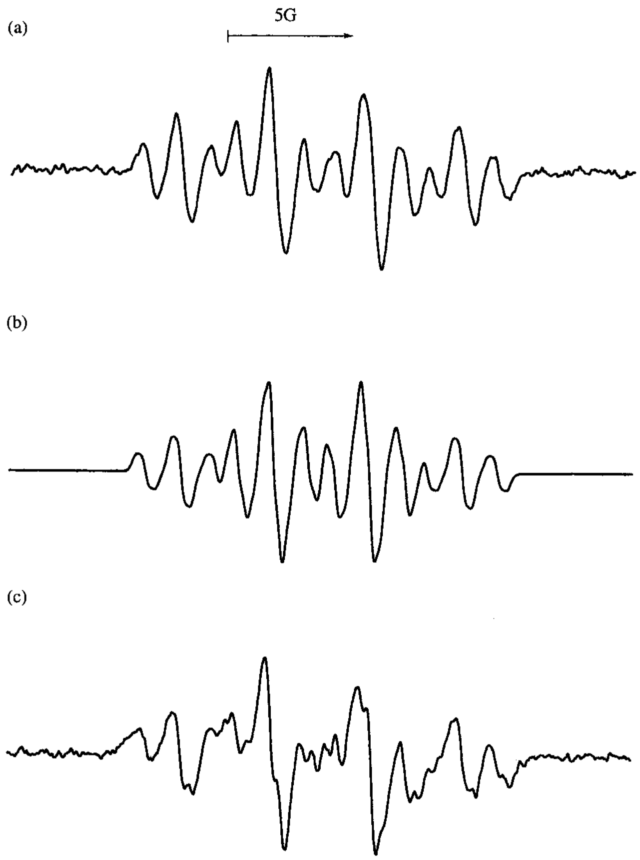
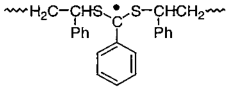


Figure 1. (a) ESR spectrum observed in the polymerization of *n*-butyl acrylate with AIBMe and **1a** in benzene at 90 °C at 4 min. (b) Computer simulation spectrum. (c) ESR spectrum observed at 9 min.

powerful tool for the investigation of paramagnetic species including organic free radicals.[16,17] The technique can yield detailed and useful information on the local structure, electronic state, and concentration of free radicals provided that their concentration is sufficiently high to be observed. In the present communication, we report on the direct ESR observations of the intermediate radicals formed during polymerizations using **1a** as the RAFT agent.

ESR measurements were performed by placing degassed solutions[18] containing freshly distilled monomer, dimethyl 2,2′-azobis(isobutyrate) (AIBMe) initiator, RAFT agent (**1a**), and benzene in the preheated cavity of the ESR spectrometer[19] at 90 °C. ESR spectra were obtained at 1 min intervals. In the case of *n*-butyl acrylate, a signal was observed after 3 min. The intensity of this signal increased with time, passing through a maximum at 11 min. Subsequently, the signal intensity decreased but remained observable throughout the experiment (1 h). The concentration of the observed radicals was estimated to be in the range of 4.0−6.0 μmol L^{-1} by calibration with 2,2,6,6-tetramethylpiperidin-1-yloxyl (TEMPO) in the same medium (*n*-butyl acrylate/benzene) and double integration of the ESR spectra at 90 °C. The poly(*n*-butyl acrylate) formed (40% conversion) had $\bar{M}_n$ 4000 and polydispersity 1.22.



(3S)

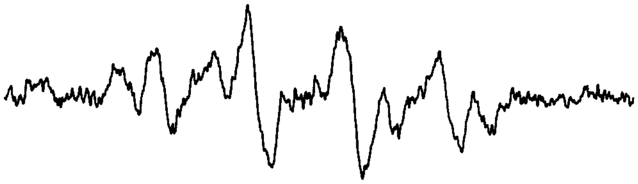
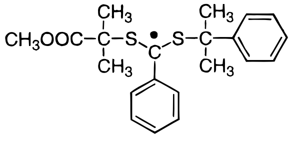


Figure 2. ESR spectrum observed in the polymerization of styrene with AIBMe and **1a** in benzene at 90 °C at 20 min.

The ESR spectrum acquired at the 4 min reaction time and a computer simulation based on the parameters listed in Table 1 are shown in Figure 1a,b, respectively. The spectrum (Figure 1a) was well-resolved and is clearly distinct from other species which could be present in the system [i.e., the propagating radical, the 2-phenylprop-2-yl (g = 2.0028)[20] derived from **1a** and the initiator-derived radical 2-(methoxycarbonyl)prop-2-yl (g = 2.0027 for 2-(isopropoxycarbonyl)prop-2-yl)[21]]. The high *g*-factor (2.0041) shows that there is a significant delocalization of the free spin onto heteroatom sites. The measured *g*-factor and hyperfine splitting values α_H are similar to those reported previously[22] for the cyclic 1,3-dithiolan-2-yl radicals **4** and **5** (see Table 1). The spectrum is thus assigned to radical **3A**. For longer reaction time, the observed ESR spectrum becomes more complex (see Figure 1c, acquired at the 9 min) but still retains the features characteristic of radical **3A** (i.e., *g*-factor, α_H constants). The additional complexity of the spectrum may be attributed to the extension of the polymer chains attached to the sulfur atoms of **3A**, the increased viscosity of the medium, or both. Further investigation is planned.

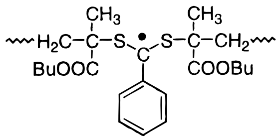
To establish that the species observed involved the monomer (*n*-butyl acrylate), a control experiment was conducted in which AIBMe and **1a** were heated in toluene solvent at 90 °C. No signals analogous to that seen in the abovementioned experiment with *n*-butyl acrylate were detectable. However, a weak spectrum attributable to 2-phenylprop-2-yl, the radical which should form on fragmentation of the RAFT adduct (**2a**)



(**2a**)

was observed. A computer simulation based on literature *g*-factor and hyperfine splitting values[20] (see Table 1) confirmed the assignment.

In the case of styrene polymerization carried out under the same conditions, an ESR spectrum (Figure 2) with hyperfine coupling constants and *g*-factor similar to those for the *n*-butyl acrylate example was observed (see Table 1). However, the spectrum was of much lower intensity corresponding to a radical concentration of ca. 0.8 μmol L^{-1}. The polystyrene formed (18% conversion) had $\bar{M}_n$ 1020 and polydispersity 1.14. The spectrum is assigned to the radical **3S**, and the lower intensity is attributed to this radical undergoing a faster rate of fragmentation than that of **3A**. In the case of *n*-butyl methacrylate, the corresponding intermediate radical **3M** was not observed. This is attributed to an even faster rate of fragmentation in the case of the radical **3M**. The poly(*n*-butyl methacrylate) formed (40% conversion) had $\bar{M}_n$ 3980 and polydispersity 1.25.



(**3M**)

The radical concentration depends on the relative rates of formation and destruction of the adduct radical (**3**). A lower radical concentration could result from either a smaller rate constant for adduct formation or higher rate constant for fragmentation. These rate constants also determine the chain transfer constant of the RAFT agent. We have found in our previous work that chain transfer constants for RAFT agents (**1**) are highly dependent on the radical leaving group ability of the R group. Both radical stability and steric factors appear to be important, and chain transfer constants decrease in the series where R is tertiary $\gg$ secondary $>$ primary and in the series where R is poly(methacrylyl) $>$ poly(styryl) $\geq$ poly(acrylyl).[11,12,23] These trends were attributed to rates of fragmentation decreasing in those series.

In summary, the intermediate radicals previously proposed to be formed during RAFT polymerizations have been observed directly by ESR.

Acknowledgment. We are grateful to Drs. C. Berge, M. Fryd and R. Matheson of DuPont Automotive Products (USA) for their support of this work.

References and Notes

(1) The use of the adjective "living" to describe a radical process that displays the attributes of a living polymerization is preferred over other terms that have been advocated in this context (e.g., "controlled", "controlled/living", "pseudo living", or "living polymerization with reversible deactivation") even though some side reactions (radical−radical termination) must inevitably complicate the process.

(2) Rizzardo, E.; Moad, G. In *The Polymeric Materials Encyclopaedia: Synthesis, Properties and Applications*; Salamone, J. C., Ed.; CRC Press: Boca Raton, FL, 1996; Vol. 5, pp 3834−3840.

(3) Matyjaszewski, K. *ACS Symp. Ser.* **1998**, *685*, 2−30. Colombani, D. *Prog. Polym. Sci.* **1997**, *22*, 1649−1720.

(4) Solomon, D. H.; Rizzardo, E.; Cacioli, P. US 4581429; *Chem. Abstr.* **1985**, *102*, 221335q.

(5) Moad, G.; Anderson, A. G.; Ercole, F.; Johnson, C. H. J.; Krstina, J.; Moad, C. L.; Rizzardo, E.; Spurling, T. H.; Thang, S. H. *ACS Symp. Ser.* **1998**, *685*, 332−360.

(6) Hawker, C. J. *Acc. Chem. Res.* **1997**, *30*, 373−382. Georges, M. K.; Veregin, R. P. N.; Kazmaier, P. M.; Hamer, G. K. *Trends Polym. Sci.* **1994**, *2*, 66−72. MacLeod, P. J.; Veregin, R. P. N.; Odell, P. G.; Georges, M. K.; *Macromolecules* **1998**, *31*, 530−531. Goto, A.; Fukuda, T. *Macromolecules* **1997**, *30*, 4272−4277. Greszta, D.; Matyjaszewski, K. *Macromolecules* **1996**, *29*, 7661−7670. Bon, S. A. F.; Bosveld, M.; Klumperman, B.; German, A. L. *Macromolecules* **1997**, *30*, 324−326. Baumert, M.; Mülhaupt, R. *Macromol. Rapid Commun.* **1997**, *18*, 787−794. Yoshida, E.; Osagawa, Y. *Macromolecules* **1998**, *31*, 1446−1453. Li, I. Q.; Howell, B. A.; Dineen, M. T.; Lyons, J. W.; Meunier, D. M.; Smith, P. B.; Priddy, D. B. *Macromolecules* **1997**, *30*, 5195−5199. Bertin, D.; Boutevin, B. *Polym. Bull. (Berlin)* **1996**, *37*, 337−344.

(7) Wang, J. S.; Matyjaszewski, K. *Macromolecules* **1995**, *28*, 7901−7910. Qiu, J.; Matyjaszewski, K. *Acta Polym.* **1997**, *48*, 169−180. Matyjaszewski, K.; Kajiwara, A. *Macromolecules* **1998**, *31*, 548−550. Matyjaszewski, K. *Macromolecules* **1998**, *31*, 4710−4717. Matyjaszewski, K. *ACS Symp. Ser.* **1998**, *685*, 258−283.

(8) Sawamoto, M.; Kamigaito, M. *Trends Polym. Sci.* **1996**, *4*, 371−377.

(9) Percec, V.; Barboiu, B.; Kim, H. J. *J. Am. Chem. Soc.* **1998**, *120*, 305−316.

(10) Haddleton, D. M.; Kukulj, D.; Duncalf, D. J.; Heming, A. M.; Shooter, A. J. *Macromolecules* **1998**, *31*, 5201−5205.

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

(12) 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*, 5559−5562.

(13) 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.*, in press.

(14) Chong, Y. K.; Le, T. P. T.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1999**, *32*, 2071−2074.

(15) Ganachaud, F.; Gilbert, R.; Monteiro, M. J.; Rizzardo, E.; Thang, S. H., unpublished results. Poly(*N*-isopropylacrylamide) sample of $\bar{M}_n$ 2530; $\bar{M}_w/\bar{M}_n$ 1.13 (polystyrene equivalent) was prepared from a radical polymerization of *N*-isopropylacrylamide (AIBN initiator at 60 °C) in the presence of benzyl dithiobenzoate as a RAFT agent.

(16) Ranby, B.; Rabek, J. F. *ESR Spectroscopy in Polymer Research*; Springer-Verlag: Berlin, 1977.

(17) Kamachi, M. *Adv. Polym. Sci.* **1987**, *82*, 207−275. Kamachi, M. *ACS Symp. Ser.* **1998**, *685*, 145−168.

(18) Stock solutions of freshly distilled monomer (0.5 mL), dimethyl 2, 2′-azobisisobutyrate (AIBMe) (10.5 mg, 4.56×10^{-5} mol) and **1a** (28.6 mg, 1.05×10^{-4} mol) in benzene (0.5 mL) were prepared. Spectra were obtained on aliquots (0.5 mL) of these solutions that had been carefully transferred into quartz ESR tubes and degassed by purging with nitrogen for 5 min and flame-sealed.

(19) ESR spectra were recorded on a Bruker ER 200D-SRC spectrometer, equipped with a universal X-band (9.4 GHz) cavity using 100 kHz field modulation, 0.5 G amplitude and 63 mW microwave power. The high power enabled rapid spectrum acquisition. Data acquisition, analysis, and simulation was performed with the Bruker EPRSRC software package.

(20) Berndt, A. in *Londolt-Bornstein − Magnetic Properties of Free Radicals*; Fischer, H., Hellwege, K.-H., Ed.; Springer-Verlag: Berlin, 1977; Vol. II/9b, p 558.

(21) Berndt, A. In *Londolt-Bornstein − Magnetic Properties of Free Radicals*, Fischer, H., Hellwege, K.-H., Ed.; Springer-Verlag: Berlin, 1977; Vol. II/9b, p 190.

(22) Gaze, C.; Gilbert, B. C. *J. Chem. Soc., Perkin Tran. II* **1979**, 763−769.

(23) Chong, Y. K.; Krstina, J.; Le, T. P. T.; Moad, G.; Rizzardo, E.; Thang, S. H. *Macromolecules* **1999**, submitted for publication.

MA990316V