

# Thioketone spin traps as mediating agents for free radical polymerization processes†

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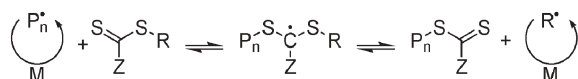
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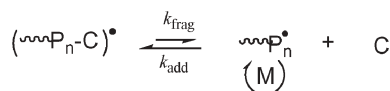
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Thioketones are demonstrated to be suitable agents for controlling free radical polymerization processes: the polymerizations carry (pseudo) living characteristics indicating that the control process is induced by a persistent radical effect.

Free radical polymerization has been revolutionized by the advent of methodologies that allow for control of the molecular weight and affect the generation of narrow polydispersity polymer. One of the most successful living free radical processes is the Reversible Addition Fragmentation Chain Transfer (RAFT) process,<sup>1,2</sup> which affects living/controlled polymerization by the establishment of an addition–transfer equilibrium between the propagating radicals and the, e.g. dithioester type, RAFT agent as follows:



In principle, the RAFT process induces living behaviour without invoking a persistent radical effect.<sup>3</sup> However, some evidence suggests that certain RAFT systems—especially those utilizing dithiobenzoates—display a persistent radical effect superimposed on the reversible addition fragmentation process.<sup>4</sup> Thus, it should be possible to design/identify reagents which allow for the isolation of the persistent radical effect and induce controlled polymerization *exclusively via* the generation of a stable intermediate radical. The general possibility of this approach (as exemplified in Scheme 1) has long been realized<sup>5</sup> and there have been some attempts to implement it into practice with somewhat limited success. In the present work we show that free radical polymerization can be controlled using thioketones as spin traps.



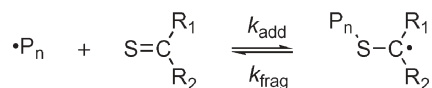
**Scheme 1** Controlled radical polymerization *via* a radical spin trap C. The propagating radicals, P<sub>n</sub>, add to C to form the stable radical P<sub>n</sub>-C.

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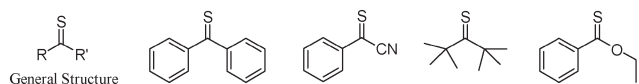
When thioketone spin traps are used to mediate free radical polymerization, the propagating radical can add to the sulfur centre of the C=S double bond as in the RAFT process:



However, unlike the RAFT process, the resulting adduct radical contains only one C–S bond that is able to undergo β-scission and there is no possibility for chain transfer. As a result, any control that is achieved must be due to storage of the propagating radical as the stabilized intermediate radical. Thioketones thus offer a useful probe for investigating the likely importance of the persistent radical effect in RAFT polymerization. More importantly, they offer a potential alternative method for controlling free radical polymerization that may help to expand the scope of current living/controlled radical processes.

For a thioketone spin trap to be employed in the specific context of free radical polymerization processes it has to fulfil a number of requirements. Most importantly, the equilibrium constant of the radical deactivation process (*K*, defined as the ratio of the addition, *k*<sub>add</sub>, to the fragmentation, *k*<sub>frag</sub>, rate coefficients) has to be relatively large in order to induce control. A series of kinetic studies into the related nitroxide mediated free radical polymerizations (NMP, which is based on the same key idea as the present process but uses a radical spin trap) indicate that *K* should be around 10<sup>9</sup> L mol<sup>-1</sup> in order to effect an efficient living process.<sup>6</sup> An equilibrium constant that is significantly below this value can still induce living behaviour, albeit with a rapid initial increase of the molecular weight<sup>7</sup> (such behaviour has been termed ‘hybrid’ behaviour in the context of the RAFT process). By the same token, the equilibrium constant should not be too large, since this can lead to severe retardation/inhibition phenomena. Ideally, the generated adduct radical should be kinetically stable towards termination with propagating radicals. While this requirement is not necessary for the spin trap to mediate the process, the cross termination reaction will contaminate final product purity and induce additional rate retardation. Likewise it is important to choose thioketones that do not undergo free radical copolymerization with the monomer.<sup>8</sup>

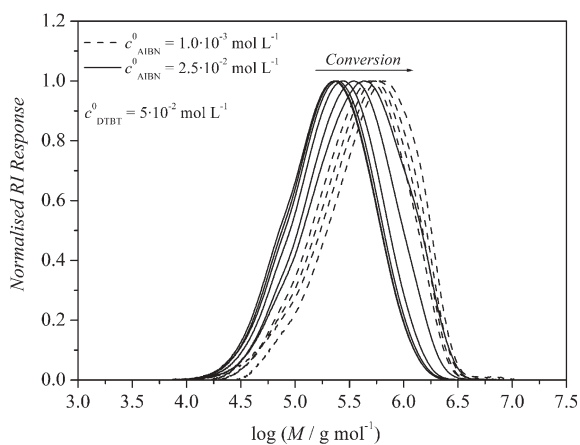
Scheme 2 depicts several thioketones that—judging exclusively from their chemical structure—may potentially be suitable for use in free radical polymerizations. Their capability to act as spin traps crucially depends on the substituents R and R', which dictate the stability of the adduct radical to β-scission and to unwanted side reactions such as bimolecular termination and propagation. In this



**Scheme 2** Selected thioketone spin traps and their general structure.

context,  $R = R' = \text{phenyl}$  and  $R = \text{phenyl}$ ,  $R' = \text{CN}$  as well as  $R = R' = t\text{-butyl}$  may be most suitable, whereas  $R = \text{phenyl}$ ,  $R' = \text{methoxy}$  (strictly speaking not a thioketone but a thioester) offers a lower degree of  $\text{C}=\text{S}$  reactivity than other thiocarbonyl compounds,<sup>9</sup> but may still be attractive for the mediation of highly reactive propagating radicals (e.g. those derived from vinyl acetate). The stability of thioketone spin traps in a non-polymerization context has been examined extensively by Scaiano and Ingold,<sup>10</sup> and subsequently by Alberti *et al.*<sup>11</sup> These authors found (*via* time resolved electron spin resonance (ESR) experiments) that the lifetimes of the adduct radicals can differ greatly depending on the chemical nature of the adding radical. For example, the addition of a *tert*-butyl radical to di-*tert*-butyl thioketone (DTBT) generates an adduct radical with a half-life of 0.8 s at 25 °C, while the adduct lifetime is extended to larger than  $10^4$  s at the same temperature when a  $\text{CF}_3$  radical is added. Nonetheless, even for the relatively stable *tert*-butyl the equilibrium constant implied by these measurements (*ca.*  $10^6 \text{ L mol}^{-1}$ )<sup>12</sup> is large enough to imply that control of polymerization may be possible with DTBT. In the present work we evaluate the ability of this agent to control styrene polymerization.

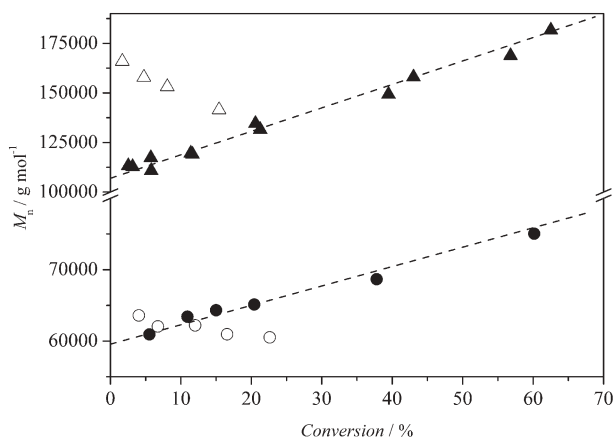
Fig. 1 depicts the evolution of the molecular weight with monomer to polymer conversion in the DTBT mediated free radical polymerization of styrene at 60 °C at two concentrations of free radical initiator 2,2'-bis(isoazobutyronitrile) (AIBN). Should the suggested mechanism (Scheme 1) be truly operational, one would expect that the molecular weight is determined by the number of initiating species in the system, identical to the concepts valid for anionic polymerization or the NMP process. Inspection of Fig. 1 indicates that the initial molecular weight is clearly controlled by the initial AIBN concentration. The corresponding control experiments (*i.e.* under the same experimental conditions, however containing no DTBT) yield molecular weight distributions that shift to *lower* molecular weights with increasing



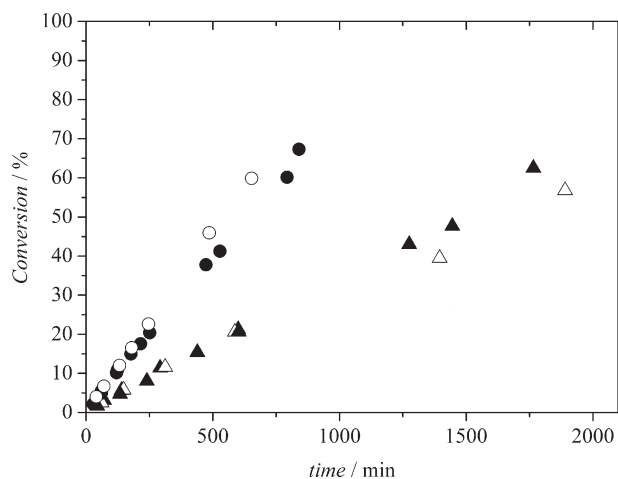
**Fig. 1** Evolution of the full molecular weight distributions in two DTBT mediated styrene bulk polymerizations at 60 °C for two initial AIBN concentrations.

monomer to polymer conversion (see below). In the DTBT–styrene system at 60 °C, the molecular weight increases initially to a relatively large value and subsequently increases with increasing conversion. Such behaviour (termed hybrid behaviour previously in the context of the RAFT process) may be indicative of a relatively small equilibrium constant (*i.e.*  $K < 10^6 \text{ L mol}^{-1}$ ) as indicated above. It must be noted that an equilibrium constant of *lower* than approximately  $1 \times 10^5 \text{ L mol}^{-1}$  will *not* lead to (pseudo) living/controlled behaviour of the polymerization system (for styrene at 60 °C).

Fig. 2 depicts the evolution of the number average molecular weight,  $M_n$ , as a function of conversion for DTBT mediated polymerizations and the corresponding control experiments containing no DTBT at otherwise unaltered reaction conditions. The notion that the equilibrium constants in the DTBT–styrene system at 60 °C are relatively small is supported by the time dependent conversion data obtained in the DTBT mediated systems and the corresponding conventional polymerization. A large equilibrium constant (*i.e.* exceeding  $10^6 \text{ L mol}^{-1}$ ) would invariably induce rate retardation effects, *i.e.* a decrease in the rate of polymerization of the DTBT system compared to the non-DTBT system, in analogy to what has been found in corresponding RAFT processes. A large equilibrium constant will lead to a high concentration of DTBT adduct radicals which are relatively slow to fragment and thus have an increased opportunity to undergo bimolecular termination reactions. Inspection of Fig. 3 clearly indicates that the DTBT system displays a rate identical to that of the non-DTBT system at the two investigated initial AIBN concentrations, indicating that  $K$  cannot exceed limits where rate retardation would be induced. Note that while the rates remain unaltered, molecular weight control is still achieved. It is important to note that the presented mechanistic picture is in good agreement with the experimental data; however, the suggested mechanism may not be complete and additional side reactions (such as termination or copolymerization) may be operational. We thus refrain from using the experimental data to deduce the equilibrium constant by a data fitting procedure at this stage. Nevertheless, the suggested mechanistic concept describes the experimental data remarkably well.



**Fig. 2** Number average molecular weight,  $M_n$ , in two DTBT mediated styrene bulk polymerizations vs. monomer to polymer conversion at 60 °C.  $c_{\text{AIBN}}^0 = 5 \times 10^{-3} \text{ mol L}^{-1}$  (triangles) and  $c_{\text{AIBN}}^0 = 2.5 \times 10^{-2} \text{ mol L}^{-1}$  (circles). The corresponding  $M_n$  resulting from the control experiments (without DTBT) are also depicted (open symbols).



**Fig. 3** Conversion vs. time evolution in two DTBT mediated styrene bulk polymerizations at 60 °C (closed symbols) and the corresponding non-DTBT polymerizations (open symbols).  $c_{AIBN}^0 = 5 \times 10^{-3}$  mol L $^{-1}$  (triangles) and  $c_{AIBN}^0 = 2.5 \times 10^{-2}$  mol L $^{-1}$  (circles). The DTBT concentration was  $5 \times 10^{-2}$  mol L $^{-1}$ .

As a further probe to assess whether the proposed control mechanism for thioketone mediated polymerization processes is physically realistic, high-level *ab initio* molecular orbital calculations of the equilibrium constants for the addition of *tert*-butyl and styryl (modelled as  $\cdot\text{CHPhCH}_2\text{CHPhCH}_3$ ) radicals to DTBT were carried out. The details of the quantum mechanical calculations can be found in the supplementary data section.† At 25 °C, we obtain an equilibrium constant for the addition of *tert*-butyl radicals to DTBT of  $7.9 \times 10^5$  L mol $^{-1}$  being in excellent agreement with the experimental data (*ca.*  $1.2 \times 10^6$  L mol $^{-1}$ ) reported by Scaiano and Ingold. Turning our attention to the experimental system, we find that at 60 °C the equilibrium constant for the addition of styryl radicals to DTBT is  $7.0 \times 10^4$  L mol $^{-1}$ . A *K* value in this range ( $10^5$  to  $10^6$ ) is consistent with the observed hybrid behaviour, and underpins the notion that the suggested molecular weight control sequence (Scheme 1) is in principle a feasible mechanistic scenario. The only other mechanistic scenario we can conceive yielding similar molecular weight evolutions is that of the thioketone acting as a very strong transfer agent (comparable to *e.g.* CBr $_4$ ) while *at the same time* rapidly decomposing. It is very unlikely that the hydrogen atoms in DTBT can be easily abstracted and that DTBT is highly unstable. Similar compound classes display transfer constants (for styrene) lower

than  $1 \times 10^{-4}$  (whereas the transfer constant for CBr $_4$  is close to 1).<sup>13</sup> Further *ab initio* calculations to design thioketones with higher equilibrium constants, their subsequent synthesis as well as employment as mediating agents is now underway.

## Notes and references

- 1 T. P. T. Le, G. Moad, E. Rizzardo and S. H. Thang, *PCT Int. Appl.*, WO 9801478 A1 980115 1998 (Chem. Abstr., 1998, **128**, 115390); D. Charmot, P. Corpart, D. Michelet, S. Z. Zard and T. Biadatti, *PCT Int. Appl.*, WO 9858974, 1998 (Chem. Abstr., 1999, **130**, 82018).
- 2 G. Moad, E. Rizzardo and S. H. Thang, *Aust. J. Chem.*, 2005, **58**, 379; C. Barner-Kowollik, T. P. Davis, J. P. A. Heuts, M. H. Stenzel, P. Vana and M. Whittaker, *J. Polym. Sci. Polym. Chem.*, 2003, **41**, 365.
- 3 P. Vana, T. P. Davis and C. Barner-Kowollik, *Macromol. Theory Simul.*, 2002, **11**, 823.
- 4 M. L. Coote and L. Radom, *J. Am. Chem. Soc.*, 2003, **125**, 1490–1491; A. Feldermann, M. L. Coote, T. P. Davis, M. H. Stenzel and C. Barner-Kowollik, *J. Am. Chem. Soc.*, 2004, **126**, 15915.
- 5 P. C. Wieland, B. Raether and O. Nyken, *Macromol. Rapid Commun.*, 2001, **22**, 700–703; D. Greszta, D. Mardare and K. Matyjaszewski, *Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.)*, 1994, **35**, 466; J. H. Epenson, *Acc. Chem. Res.*, 1992, **25**, 222.
- 6 See for example: A. Goto and T. Fukuda, *Prog. Polym. Sci.*, 2004, **29**, 329.
- 7 C. Barner-Kowollik, J. F. Quinn, T. L. U. Nguyen, J. P. A. Heuts and T. P. Davis, *Macromolecules*, 2001, **34**, 7849.
- 8 Some means of end-capping the final polymer species with a useful functional group is also desirable for a practical process. This could be achieved through the addition of a large excess of chain transfer agent or some other terminating species at the conclusion of the polymerization. In the present (preliminary) study, we merely isolate the polymer at the conclusion of the process and allow it to terminate ‘naturally’ (*i.e.* it is envisaged that most free carbon-centred propagating radicals undergo bimolecular termination to yield a polymer chain with 2 cyanoisopropyl end groups, as per conventional polymerization). As a result, the structure of the polymeric products generated *via* thioketone mediated polymerization are polymer chains capped with an initiator end-group on both sides, *i.e.* chains that have undergone bimolecular termination.
- 9 A. Alberti, M. Benaglia, A. Hudson, D. Macciantelli and S. Masson, *Res. Chem. Intermed.*, 2001, **27**, 659–668.
- 10 J. C. Scaiano and K. U. Ingold, *J. Am. Chem. Soc.*, 1976, **98**, 4727–4732.
- 11 A. Alberti, M. Benaglia, B. F. Bonini and G. F. Pedulli, *J. Chem. Soc., Faraday Trans. 1*, 1988, **84**, 3347–3358.
- 12 Scaiano and Ingold (ref. 10) report a half-life for the adduct radical formed by the reaction of DTBT with *tert*-butyl radical of 0.8 s (which corresponds to a rate constant of  $0.866$  s $^{-1}$  at 25 °C. Combining this with an addition rate coefficient of  $106$  L mol $^{-1}$  s $^{-1}$  (see ref. 10 as well as the numbers reported in various studies for the (almost barrierless) addition of radicals to dithioester compounds), one obtains *K* as  $1.2 \times 10^6$  L mol $^{-1}$ .
- 13 *Polymer Handbook*, ed. J. Brandrup, E. H. Immergut and E. A. Grulke, John Wiley and Sons NY, New York, 4th edn, p. II/97.