

Supplementary Information:

Spin Capturing with Nitrones: Radical Coupling Reactions with Concurrent Introduction of Midchain Functionality

Edgar H. H. Wong,^{a,b} Cyrille Boyer,^b Martina H. Stenzel,^b
Christopher Barner-Kowollik^{*a} and Thomas Junkers^{*a}

^a Preparative Macromolecular Chemistry, Institut für Technische Chemie und Polymerchemie, Karlsruhe Institute of Technology (KIT), Engesserstr. 18, Geb. 11.23, 76128 Karlsruhe, Germany.

^b Centre for Advanced Macromolecular Design (CAMD), School of Chemical Sciences and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia.

E-mail: christopher.barner-kowollik@kit.edu, thomas.junkers@kit.edu
^{*}Corresponding authors, Tel:(49)-721-6085641, Fax: (+49)-721-6085740

Experimental Section

Materials. Methyl 2-bromopropionate (MBrP, Aldrich, 98 %), *N,N,N',N',N''*-pentamethyldiethylenetriamine (PMDETA, Aldrich, 99 %), *N*-tert-butyl- α -phenylnitron (PBN, Aldrich, 98 %), butyl acetate (Sigma-Aldrich, 99 %), copper (II) bromide (Sigma-Aldrich, 99 %), copper powder < 75 μ m (Cu(0), Aldrich, 99 %), toluene (Aldrich, 99.9 %), tributyl tin hydride (TBTH, Aldrich, 97 %), tetrahydrofuran (THF, Sigma, 99 %) and dimethyl formamide (DMF, Aldrich, 99.8 %) were used as received. Styrene (Sty, Aldrich, 99 %) and isobornyl acrylate (*i*BoA, Aldrich) monomers were de-inhibited by percolating over a column of basic alumina. Copper (I) bromide (CuBr, Sigma-Aldrich, 98 %) was washed with glacial acetic acid at 80 °C for overnight to remove any soluble oxidized species before being filtered, rinsed with ethanol and dried.

Synthesis of PS I by ATRP. To a 100 mL round bottom flask that contains CuBr (143 mg), Sty (50 mL) and MBrP (112 μ L) were added and the solution was degassed by purging with nitrogen for 30 minutes in an ice bath. Degassed PMDETA (418 μ L) was transferred into the flask via a degassed syringe. The reaction mixture was heated at 100 °C in a thermostated oil-bath for 40 minutes and the polymerization was stopped by immersing the sealed flask in an ice bath before opening to air. A sample

was withdrawn from the solution and analysed by NMR to determine the conversion (~ 10 % monomer conversion was obtained). The contents in the flask were poured into a beaker containing CuBr₂ (500 mg) in THF and was left overnight in vacuum to remove any unreacted styrene. Fresh THF was then added to the beaker and the polymer PS **I** was purified by passing the polymer solution over a column of silica gel in order to remove all copper complexes. The copper-free polymer solution was subsequently concentrated and precipitated in cold methanol yielding 3.5 g of polymer with $M_n = 2800 \text{ g}\cdot\text{mol}^{-1}$ and $PDI = 1.11$ (by THF-SEC analysis).

Synthesis of PiBoA I by ATRP. PiBoA **I** was synthesized in a similar manner to PS **I**. To a 50 mL round bottom flask that contains CuBr (100 mg), *i*BoA (15 mL) and MBrP (52 μL) were added and the solution was degassed by purging with nitrogen for 10 minutes in an ice bath. A degassed solution of 5 mL butyl acetate with PMDETA (294 μL) was transferred into the flask via a degassed syringe. The reaction mixture was heated at 75 °C in a thermostated oil-bath for 15 minutes and the polymerization was stopped by immersing the sealed flask in an ice bath before opening to air. A sample was withdrawn from the solution and analysed by NMR to determine the conversion (~ 20 % monomer conversion was obtained). The contents in the flask were poured into a beaker containing CuBr₂ (250 mg) in THF and was left overnight in vacuum to remove any solvent. Fresh THF was then added to the beaker and the polymer PiBoA **I** was purified by passing the polymer solution over a column of silica gel in order to remove all copper complexes. The polymer solution which was then free of copper complexes was concentrated and subsequently reprecipitated twice in cold methanol yielding 1.8 g of polymer with $M_n = 4400 \text{ g}\cdot\text{mol}^{-1}$ and $PDI = 1.29$ (by THF-SEC analysis).

Synthesis of PiBoA IV by ATRP. PiBoA **IV** was synthesized in a similar manner to PS **I**. To a 50 mL round bottom flask that contains CuBr (50 mg), *i*BoA (7.5 mL) and MBrP (26 μL) were added and the solution was degassed by purging with nitrogen for 10 minutes in an ice bath. A degassed solution of 2.5 mL butyl acetate with PMDETA (147 μL) was transferred into the flask via a degassed syringe. The reaction mixture was heated at 75 °C in a thermostated oil-bath for 75 minutes and the polymerization was stopped by immersing the sealed flask in an ice bath before opening to air. A sample was withdrawn from the solution and analysed by NMR to determine the

conversion (~ 70 % monomer conversion was obtained). The contents in the flask were poured into a beaker containing CuBr₂ (150 mg) in THF and was left overnight in vacuum to remove any solvent. Fresh THF was then added to the beaker and the polymer PiBoA **IV** was purified by passing the polymer solution over a column of silica gel in order to remove all copper complexes. The copper-free polymer solution was concentrated and subsequently reprecipitated twice in cold methanol yielding 4 g of polymer with $M_n = 14300 \text{ g}\cdot\text{mol}^{-1}$ and $PDI = 1.19$ (by THF-SEC analysis).

Radical–Radical Conjugation Reactions with PBN. As a general procedure, 0.1 mmol of an ATRP-made polymer, 0.5 mmol of PBN (5 eq.) and 0.1 mmol (1 eq.) of copper powder were dissolved in 800 μL of toluene in a glass vial (to make up a 0.1 M solution of the ATRP polymer) and purged with nitrogen for 10 minutes in an ice bath. In the case of PiBoA **I** and PiBoA **IV**, 5 eq. and 0.5 eq. of PBN, respectively, are sufficiently for the conjugation reactions. A degassed solution of 200 μL with PMDETA (0.1 mmol, 1 eq.) was transferred into the glass vial via a degassed syringe. The reaction mixture was heated to 60 °C in an electrical thermomixer for 3 hours. The resulting conjugated polymer was purified by passing over a column of silica gel and reprecipitated twice in cold methanol before being analysed by NMR and THF-SEC.

Polymer Quenching. In a typical procedure, for example, 10 μmol of PS **II** was dissolved in 538 μL of DMF before adding 2 mmol of TBTH (538 μL) such that the ratio of polymer to quencher is 1:200. The solution was heated to 125 °C for 5 hours. Under these conditions, the alkoxyamine bond is cleaved and TBTH transfers its proton to the radicals preventing recombination. As the hydride is a strong transfer agent, quantitative quenching can be assumed considering the high concentration of quencher and the relatively high temperature. The solvent was removed by evaporation in a fume cupboard before the quenched polymer was analysed via THF-SEC. Quenching of the PiBoA samples was carried out analogous.

Characterization by THF Size Exclusion Chromatography (THF-SEC). Analysis of the molecular weight distributions of the polymer samples were performed on a Polymer Laboratories PL-GPC 50 Plus Integrated System, comprising an autosampler, a PLgel 5.0 μm bead-size guard column (50 x 7.5 mm), followed by three PLgel 5 μm

Mixed-C columns (300 x 7.5 mm) and a differential refractive index detector using tetrahydrofuran (THF) as the eluent at 35 °C with a flow rate of 1 mL·min⁻¹ was used. The SEC system was calibrated using linear narrow polystyrene standards ranging from 160 to 6·10⁶ g·mol⁻¹ (polystyrene ($K = 14.1 \cdot 10^{-5}$ dL·g⁻¹ and $\alpha = 0.70$),¹ poly(isobornyl acrylate) ($K = 5.0 \cdot 10^{-5}$ dL·g⁻¹ and $\alpha = 0.745$)²). Polymer concentrations were in the range of 3 – 5 mg·mL⁻¹.

Characterization by ¹H-NMR. NMR measurements were performed using a Bruker AM 400 MHz spectrometer for hydrogen nuclei. All samples were dissolved in CDCl₃. The δ-scale is referenced to tetramethylsilane (δ = 0.00) as internal standard.

¹H-NMR Results

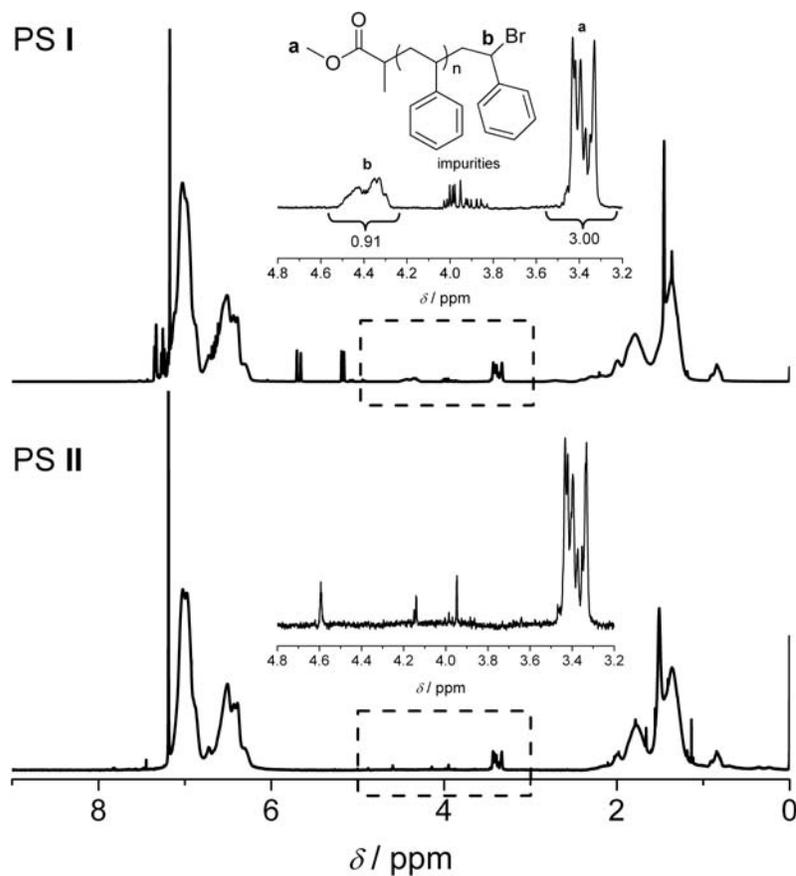


Figure S1. ¹H-NMR spectra of PS I and PS II. The insets show zooms into the NMR spectra for the region between $\delta = 3.2 - 4.8$ ppm. The numbers below the peaks a and b in the zoom of PS I correspond to the integrals of the peaks.

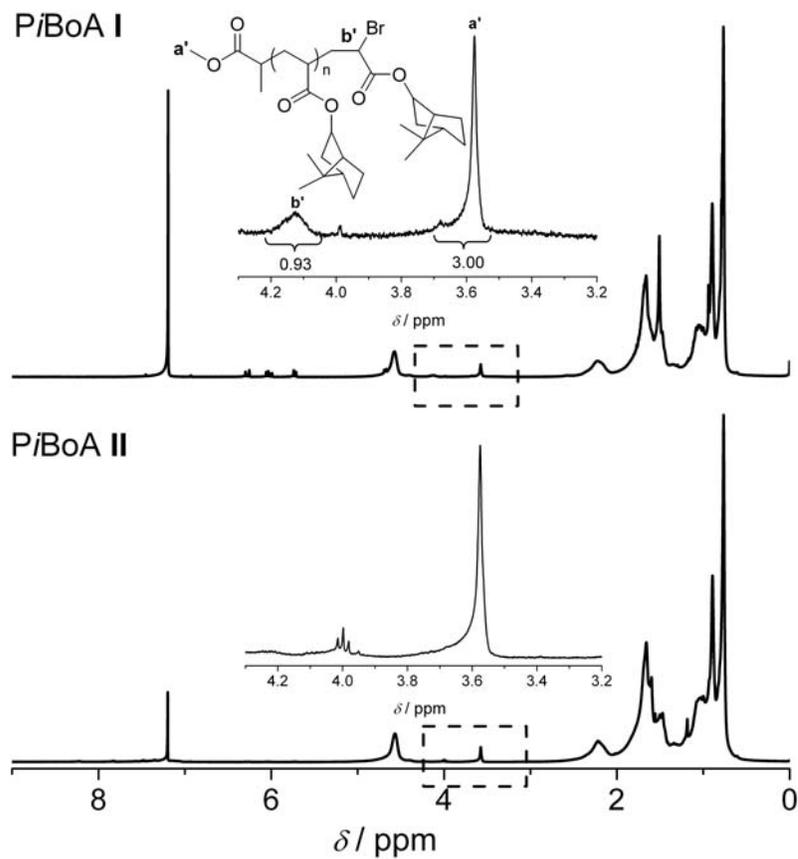


Figure S2. ^1H -NMR spectra of P/BoA I and P/BoA II. The insets show zooms into the NMR spectra for the region between $\delta = 3.2 - 4.3$ ppm. The numbers below the peaks a' and b' in the zoom of P/BoA I correspond to the integrals of the peaks.

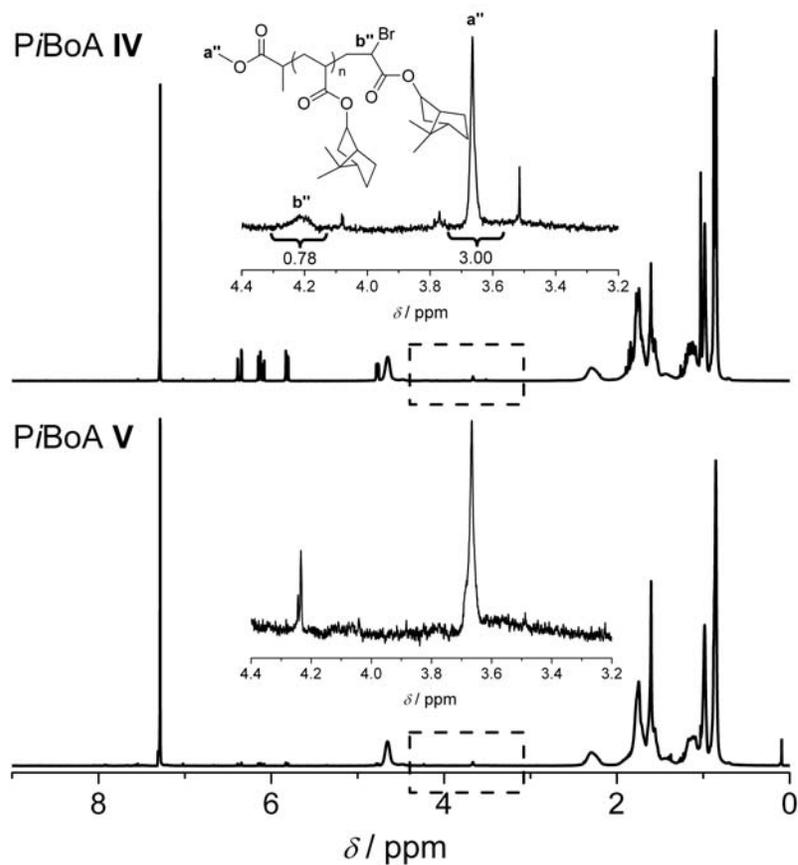
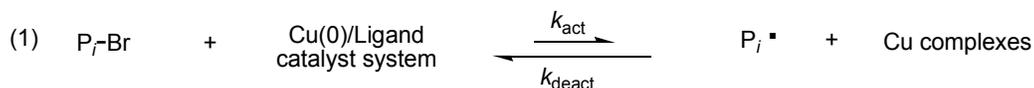


Figure S3. $^1\text{H-NMR}$ spectra of P/BoA IV and P/BoA V. The insets show zooms into the NMR spectra for the region between $\delta = 3.2 - 4.4$ ppm. The numbers below the peaks a'' and b'' in the zoom of P/BoA IV correspond to the integrals of the peaks.

PREDICI® Simulation Results – Determining Kinetic Limits

Macroradical generation



Nitron capturing



Conventional bimolecular termination



Scheme S1. Reaction scheme assumed for the PREDICI simulation of the radical-radical conjugation reactions.

Reactions 1 to 4 in Scheme S1 were adopted for the simulation of the nitron-mediated radical conjugation reactions. The model reflects the simplicity of the actual experimental system and a few equations are sufficient to describe the kinetic scenario. Namely, the reaction steps are (i) activation of the ATRP polymers to generate macroradicals (reaction 1), (ii) consumption of macroradicals via spin capturing from a nitron (reaction 2), (iii) spin annihilation of a macronitroxide with a second macroradical chain and (iv) termination by conventional radical combination (reaction 4). For the model, the assumption was made that reaction 4 only proceeds via combination, although this is not necessarily true. However, for the outcome of the modelling, differentiation between combination and disproportionation is of no larger influence. Additionally, no chain length dependency of the kinetic rate coefficients was assumed. The kinetic rate parameters employed for this model are collated in Table S1 (for 60 °C). k_{act} is the rate coefficient for the activation of ATRP polymers, k_{deact} is the rate coefficient for the deactivation step in ATRP. k_t is the termination rate coefficient for conventional bimolecular termination, k_c is the rate coefficient of the

combination between macroradicals and macronitroxide. $k_{\text{ad,macro}}$ is the rate coefficient of the addition of macroradicals to the nitron. c_{nitron} is the initial nitron concentration and c_{P} is the concentration of the starting ATRP polymer. All kinetic rate coefficients are based on literature values for (poly)styrene.

Table S1. Kinetic rate parameters in the input of the PREDICI simulation model. All units are in $\text{L}\cdot\text{mol}^{-1}\cdot\text{s}^{-1}$ unless given otherwise.

k_{act}	$k_{\text{deact}}^{\text{a}}$	k_{t}^{b}	k_{c}	$k_{\text{ad,macro}}^{\text{c}}$	c_{nitron}	c_{P}^{d}
1×10^{-3}	1×10^7	1×10^8	1×10^9	580	$0.5 \text{ mol}\cdot\text{L}^{-1}$	$0.1 \text{ mol}\cdot\text{L}^{-1}$

^aApproximate model assumption based on ref. [3].

^bApproximate model assumption based on ref. [4].

^cActual value taken from ref. [5, 6] for a Sty system at 60 °C .

^dTrue experimental value used in this work.

The aim of the modelling is to elucidate, under which conditions the target product, that is the alkoxyamine bridged coupling product from reaction 3, is predominantly formed. On first glance, one might assume that the composition of the product mixture depends on the competitive rate of reaction 3 and 4. However, as k_{c} and k_{t} are most likely similar in most systems, the addition rate of macroradicals to the nitron must be seen as the determining reaction step. In fact, when a steady state of the macronitroxide radical concentration is assumed, then the expression $k_{\text{ad,macro}}\cdot c_{\text{nitron}} = k_{\text{c}}\cdot c_{\text{macronitroxide}}$ holds true. In consequence, the absolute rate of reaction 3 is influenced by the initial nitron concentration, while reaction 4 is only determined by the macroradical concentration, and thus by reaction 1 in which this species is generated. Thus, the true competition that determines which product is obtained is between reaction 1 and 2. It should be noted that the kinetic scenario is relatively similar to the one of Enhanced Spin Capturing Polymerization, ESCP, with the difference being conventional initiation and chain propagation being active instead of radical generation from the ATRP polymer. Thus, in general, similar dependencies as for ESCP can be expected as an outcome from the simulations in the framework of this study. For more details on the kinetic dependencies, the reader is referred to ref.⁷

Figure S4 below shows the amount of mid-chain functionalized polymer, $P_{\text{i-NO-}P_{\text{j}}}$, and dead polymers, P_{ij} , that are formed when different k_{act} values are assumed

(at a constant k_{deact}). It is also worth mentioning that the initial ratio of c_{nitron} to c_{P} is thereby kept constant at 5:1. Evidently, a high fraction of the desired mid-chain functionalized polymer $P_i\text{-NO-}P_j$ is only achievable when k_{act} is small, which from an experimental point of view can be translated as a 'slow release' of macroradicals from the ATRP polymer. An overall small c_{R} favours macroradical addition to the nitron over direct termination as the nitron concentration is at all times much larger than the radical concentration. In practice, the release rate of reaction 1 is not only given by k_{act} , but also dependable on the choice of ligand, solvent, active copper surface area and temperature. It is however difficult to determine the extent of the influence of all these individual variables. However, for the simulation model it is suffice to vary k_{act} (while keeping k_{deact} constant) in order to simulate the rate of release of macroradicals in an actual system. Thus, a small k_{act} can also be interpreted by using a less active ligand system or copper with a smaller active surface area.

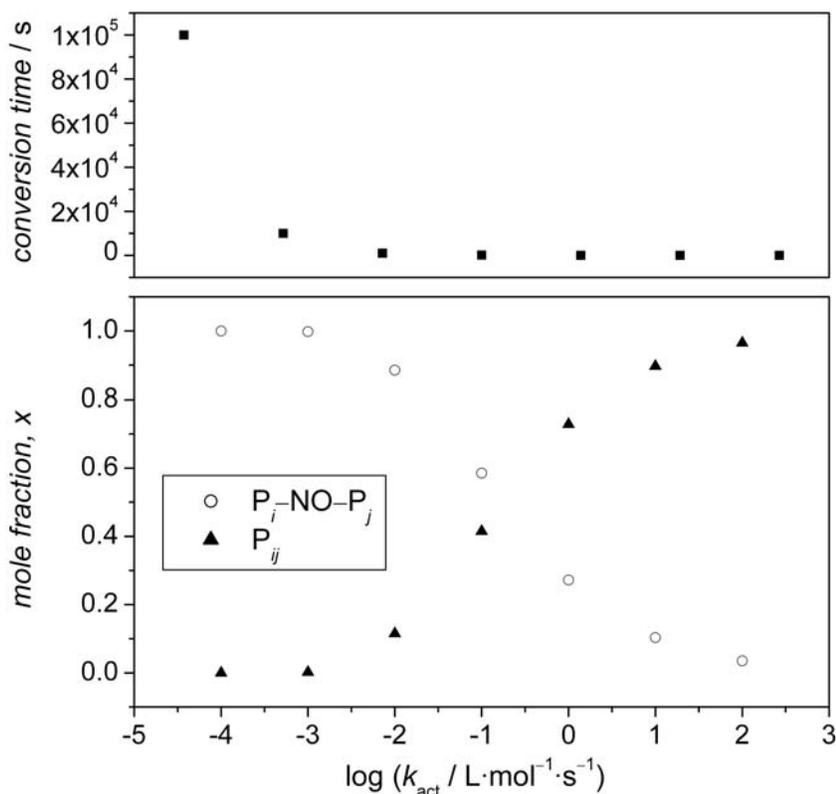


Figure S4. Variation in the mole fractions between the mid-chain functionalized polymer $P_i\text{-NO-}P_j$ and the dead polymer P_{ij} with respect to the activation rate coefficient, k_{act} . The top part shows the total conversion time for the transformation of the initial ATRP polymer.

Another observation that can be made from Figure S4 is the decrease in overall conversion time with higher k_{act} values and vice versa. This is not at all surprising since ATRP polymers are more rapidly consumed when a large excess of copper and/or ligand is employed.

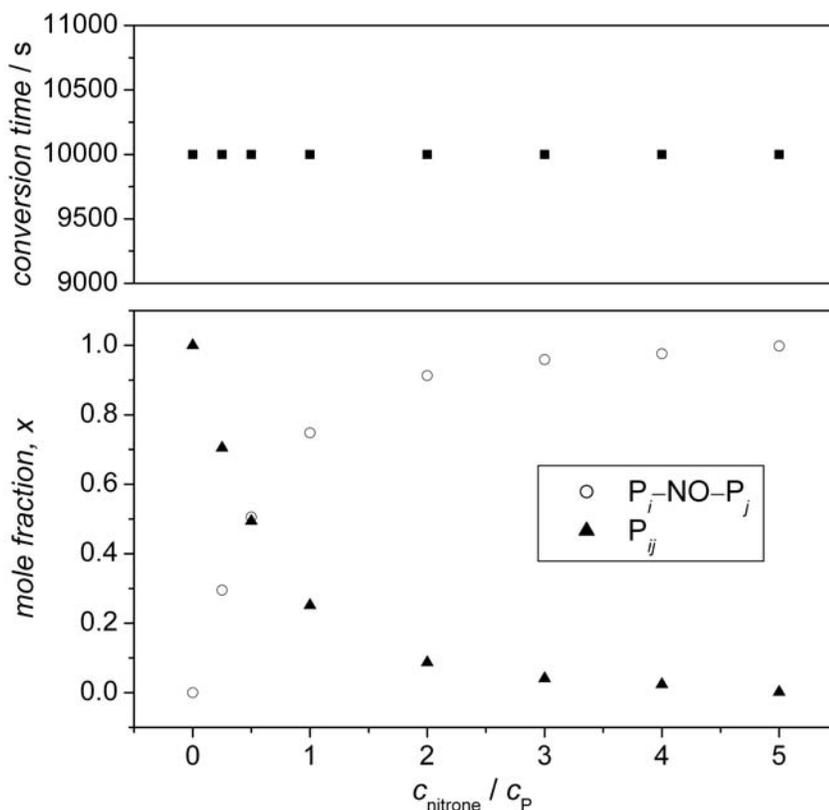


Figure S5. Variation in the mole fractions between mid-chain functionalized polymer and dead polymer with the ratio of nitrone concentration to ATRP polymer concentration, $c_{\text{nitron}}/c_{\text{P}}$. The top part shows the plot of conversion time versus $c_{\text{nitron}}/c_{\text{P}}$.

In Figure S5, the influence of the nitrone concentration, c_{nitron} , on the amount of mid-chain functionalized polymer produced is shown. For the simulation, c_{P} was kept constant and only c_{nitron} was varied. Not surprisingly, the reaction is pushed in the desired direction by increasing the nitrone content in the initial reaction mixture (and thus by increasing the rate of reaction 2). The time to reach full conversion remains constant as k_{act} was not varied. The conversion time for this case is about 10000 s ($< 3\text{h}$), which is generally in good agreement with real time. 100 %

functionalization can be only be achieved at $c_{\text{nitron}}/c_{\text{P}} = 5$. At $c_{\text{nitron}}/c_{\text{P}} = 0.5$, which is the stoichiometric amount of nitron, only about 50 % functionalized polymer is obtained. The situation can be improved, however, by a lowering of the k_{act} value in order to attain a slower rate of release of macroradicals, which would then of course lead to longer conversion times. By doing so, the overall radical concentration is decreased, which again favours reaction 2 over reaction 4.

Alternatively, full functionalization can be achieved by choosing a system in which $k_{\text{ad,macro}}$ is higher than for polystyryl radicals. Simulations on what $k_{\text{ad,macro}}$ is required for such task, a variation of this rate coefficient was carried out and the results can be seen in Figure S6.

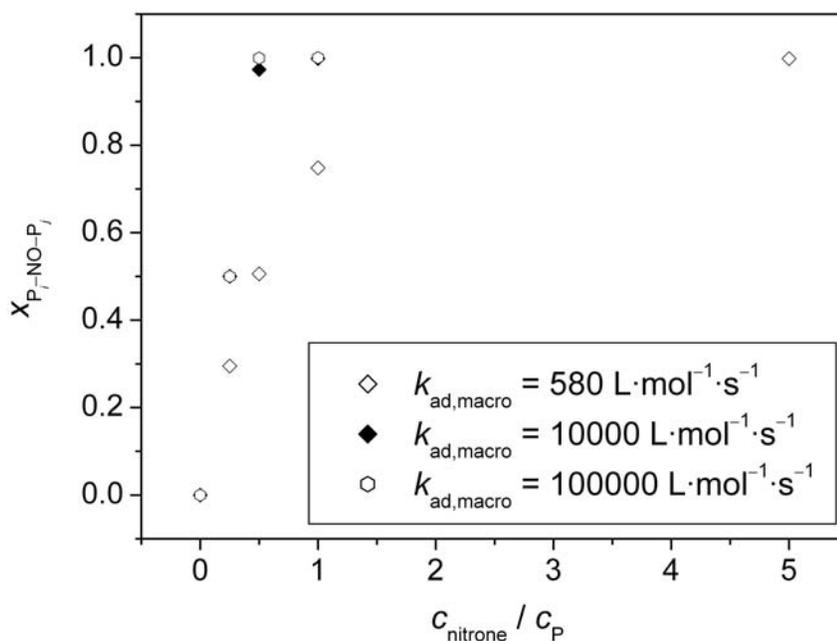


Figure S6. The difference in the ratio of nitron to ATRP polymer needed to achieve high concentration of mid-chain functionalized polymer for three different $k_{\text{ad,macro}}$ values.

Figure S6 shows the variation of mid-chain functionalized polymer with different amounts of c_{nitron} (at a constant c_{P}) for three different $k_{\text{ad,macro}}$ values (and constant k_{act}). As described above, when an addition rate as with polystyryl radicals is assumed ($580 \text{ L}\cdot\text{mol}^{-1}\cdot\text{s}^{-1}$), 5 equivalents of nitron to ATRP polymer are required to reach 100 % formation of alkoxyamine-bridged polymers. As expected, when $k_{\text{ad,macro}}$ is increased, more than 95 % functionalization can be achieved at the minimal amount

of nitron, e.g. 0.5 eq. while keeping the rate of radical release (k_{act} and k_{deact}) from the ATRP polymer (and thus the time required for complete conversion) constant. Thus, for acrylate type macroradicals, which exhibit addition rates in the order of $10^5 \text{ L}\cdot\text{mol}^{-1}\cdot\text{s}^{-1}$, full conversion under retention of close to 100% functionality can be achieved without compromising the reaction time.⁶ If polystyrene (or any other type of polymer with small radical addition rates) is supposed to be converted via the nitron-mediated coupling method, either, a sufficient excess of nitron must be employed (as was done in the framework of the present study), or the radical release rate and thus average radical concentration must be diminished leading to extended reaction times.

References

- [1] Strazielle, C.; Benoit, H.; Vogl, O. *Eur. Polym. J.* **1978**, *14*, 331-334.
- [2] Dervaux, B.; Junkers, T.; Schneider-Baumann, M.; Du Prez, F.E.; Barner-Kowollik, C. *J. Polym. Sci. – Polym. Chem.* **2009**, *47*, 6641–6654.
- [3] Ohno, K.; Goto, A.; Fukuda, T.; Xia, J.; Matyjaszewski, K. *Macromolecules* **1998**, *31*, 2699 – 2701.
- [4] Buback, M.; Kuchta, F. D. *Macromol. Chem. Phys.* **1997**, *198*, 1455–1480.
- [5] Wong, E. H. H.; Junkers, T.; Barner-Kowollik, C. *J. Polym. Sci. Part A: Polym. Chem.* **2008**, *46*, 7273 – 7279.
- [6] Wong, E. H. H.; Stenzel, M. H.; Junkers, T.; Barner-Kowollik, C. *J. Polym. Sci. Part A: Polym. Chem.* **2009**, *47*, 1098 – 1107.
- [7] Junkers, T.; Wong, E. H. H.; Stenzel, M. H.; Barner-Kowollik, C.; *Macromolecules* **2009**, *42*, 5027–5035.