Orthogonal Modification of Polymers via Thio−Bromo "Click" Reaction and Supramolecular Chemistry: An Easy Method Toward Head-to-Tail Self-Assembled Supramolecular Polymers

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Ⓢ Supporting Information

ABSTRACT: Heterotelechelic poly(n-butyl acrylate)s (PnBuA) bearing two different and complementing supramolecular groups (namely, barbiturate (Ba) and the Hamilton wedge (HW)) at their α-end and ω-end (Ba−PnBuA−HW) were prepared by a combination of the reversible addition−fragmentation chain transfer (RAFT) process and the thio−bromo click reaction. The successful synthesis of the heterotelechelic H-bonding polymer Ba−PnBuA−HW ($M_{n,NMR}$ = 7700 g/mol, $M_{n,SEC}$ = 7500 g/mol, PDI = 1.25) was proven by a combination of ^{1}H NMR and MALDI-TOF mass spectrometry. Self-assembly of the resulting heterotelechelic H-bonding polymers (Ba−PnBuA−HW) in a head-to-tail fashion driven by multiple H-bondings in solution and in the bulk was proven by temperature-dependent ^{1}H NMR, concentration-dependent DOSY NMR studies, and rheological measurements.
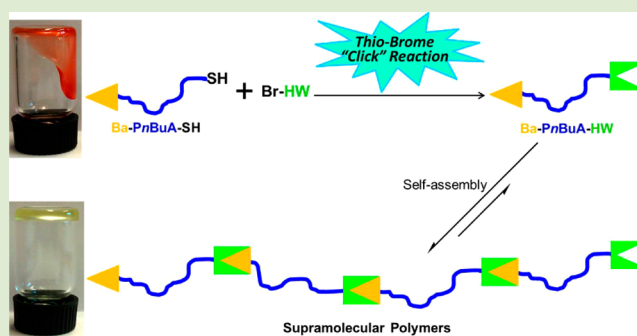
Postpolymerization modification is a straightforward strategy to implement versatile functionality onto a polymer backbone.[1−4] Although widespreadly employed, steric hindrance of the polymer backbone often results in many postpolymerization modifications suffering from incomplete functionalization. To overcome this issue, "clicking"[5−11] on polymers has been exploited and used as an attractive and efficient option over the past decade.[2,3,10] The great successes of click/highly efficient coupling reactions in polymer science, such as the popular azide−alkyne cycloaddition (CuAAC), the Diels−Alder, the hetero Diels−Alder and a series of thiol-based reactions, including the thiol−ene/yne, thiol−isocyanate, and thiol−epoxy reactions, were comprehensively summarized and highlighted recently.[2,3,10,12,13] However, as the final "click" reactions not exclusively decide the overall efficiency of the functionalization but also on the efficiency of functional group attachment before the "click" reaction, only a few "click" chemistries have found broad application in polymer science.[3,9,10]

Thus, the exploration of the CuAAC for the attachment of H-bonding moieties onto polymers, combined with ring-opening metathesis polymerization (ROMP),[14] living carbocationic polymerization (LCCP),[15,16] nitroxide-mediated radical polymerization (NMP),[17] ring-opening polymerization (ROP),[18] or atom transfer radical polymerization (ATRP),[19,20] has enabled us to successfully introduce different H-bonding moieties (such as diamino-triazine, thymine, Hamilton wedge, barbiturate, or the 2-ureidopyrimidinone

(UPy)[21,22]) into various polymers. On the other hand, the robust thio−bromo click reaction, first reported by Percec and co-workers in 2009, has successfully allowed efficient divergent dendrimer synthesis.[23,24] Lowe and co-workers subsequently have described the generation of covalent multiblock and hyperbranched polymers by a combination of the thio−bromo click reaction and RAFT polymerization.[25] Although several other successful examples[26,27] have been demonstrated more recently, the thio−bromo click reaction as a young member in the big family of click/highly efficient coupling reactions has been far less explored in comparison to others so far.[12]

In this work, we for the first time present a highly efficient synthesis of head-to-tail self-assembled supramolecular polymers relying on the combination of a RAFT process, the thio−bromo click reaction, the CuAAC, and supramolecular chemistry (Scheme 1). The prominent Ba/HW couple has been chosen due to its high bonding constant (K_{ass} = ∼10^5 M^{-1} in toluene at 30 °C[28]), therefore expecting a α-Ba, ω-HW functionalized heterotelechelic H-bonding polymer, Ba−PnBuA−HW, to self-assemble via a head-to-tail arrangement under formation of repetitive regular sequence (Scheme 1).[29−34] Thus, besides cyclic polymers, preferably linear
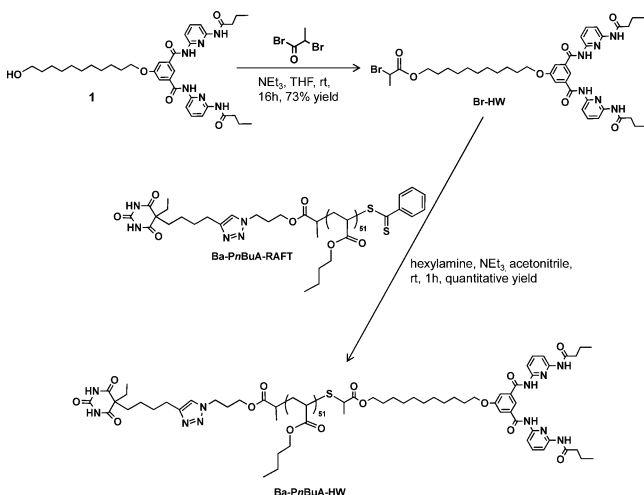
Scheme 1. General Strategy for the Synthesis of Head-to-Tail Self-Assembled Supramolecular Ba−PnBuA−HW Polymers
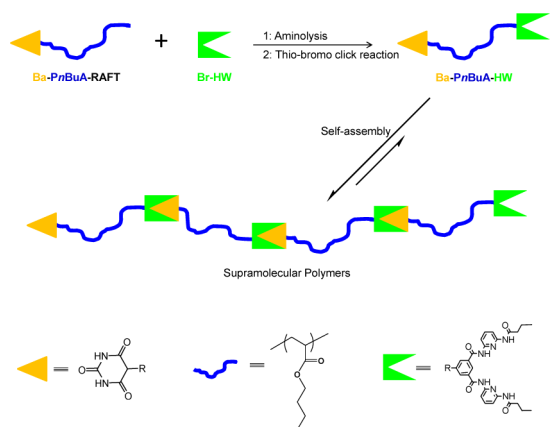
alternating polymers should be formed at higher concentrations or in the melt.[35]

Aiming at fabricating the heterotelechelic H-bonding polymer Ba−PnBuA−HW (Figure 1), we first prepared a

Figure 1. Synthetic route to the α-Ba, ω-HW functionalized heterotelechelic H-bonding polymer Ba−PnBuA−HW.

bromoester bearing the Hamilton wedge, i.e., Br−HW, via an esterification reaction between compound **1** and 2-brompropionyl bromide. The introduction of the HW moiety was confirmed by ^{1}H NMR with the appearance of a peak corresponding to the formation of an ester moiety at 4.08 ppm as well as the presence of characteristic peaks of the HW (Figures S1 and S2, Supporting Information). Meanwhile, the α-Ba functionalized polymer Ba−PnBuA−RAFT ($M_{n,NMR}$ = 7100 g/mol, $M_{n,SEC}$ = 6800 g/mol, PDI = 1.27) was synthesized according to previous work.[36]

Subsequently, the ω-dithiobenzoate end groups of the Ba−PnBuA−RAFT were tailored by affixing the HW via an aminolysis reaction of the RAFT agent, followed by a robust thio−bromo click reaction in a one-pot reaction (Figure 1). After purification by simple precipitation in cold MeOH/H2O (1/1, v/v), the successful transformation of Ba−PnBuA−RAFT to Ba−PnBuA−HW was first proven by ^{1}H NMR (Figure 2). Comparing the spectrum of Ba−PnBuA−RAFT, the complete disappearance of the characteristic phenyl protons (7.38, 7.54,
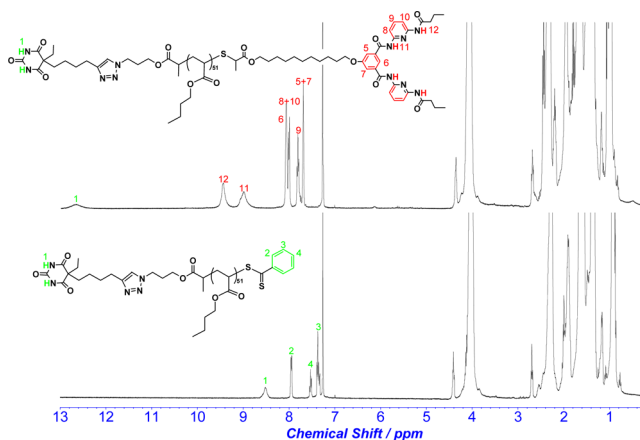
Figure 2. ^{1}H NMR spectra of Ba−PnBuA−RAFT (bottom) and Ba−PnBuA−HW (top) at 27 °C in CDCl3 (c = 3 mM).

and 7.94 ppm in Figure 2, bottom) ortho to the dithiobenzoate group, along with the appearance of the Hamilton wedge NH protons (8.99 and 9.41 ppm in Figure 2, top), as well as pyridyl and phenyl protons (7.68, 7.78, and 7.97−8.05 ppm in Figure 2, top, and Figure S4, Supporting Information), supported the successful attachment of the Hamilton wedge onto the polymer chain ends.

The structures of Ba−PnBuA−RAFT and Ba−PnBuA−HW were further studied by MALDI-TOF MS spectrometry. Both mass spectra were observed in the linear mode and by ionization of chains assisted with dithranol as the matrix and NaI as the cationizing agent (Figure 3). Comparing the MALDI
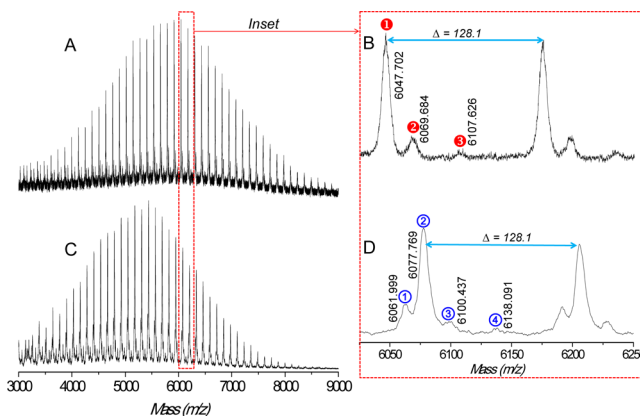

Figure 3. MALDI-TOF MS of Ba−PnBuA−HW (A) full spectrum and (B) expansion, and Ba−PnBuA−RAFT (C) full spectrum and (D) expansion.

spectrum of Ba−PnBuA−HW (Figure 3A) to Ba−PnBuA−RAFT (Figure 3C), the shift toward high molar mass indicated the successful attachment of the HW moiety. Both MALDI-TOF spectra (Figure 3B and D) underlined the presence of a singly charged main series (red solid ① and blue open ② for Ba−PnBuA-HW and Ba−PnBuA-RAFT, respectively), along with other minor series (red solid ② and ③ and blue open ①, ③, and ④): each set of ions was separated by 128.1 g/mol, reflecting the repeating unit of the nBuA monomer (calculated 128.08 g/mol). Detailed simulations of MALDI-TOF MS spectrometry for both Ba−PnBuA−HW and Ba−PnBuA−RAFT were given in Figures S5 and S6 (Supporting Information), proving the complete macromolecular trans-

formation via the thio−bromo click methodology. Altogether, these results clearly demonstrated that a quantitative linkage of two large reactive parts was achieved, similar to "click"-based strategies using simple[3] or complicated[37] functional end groups.

With the expected Ba−PnBuA−HW in hand, the self-assembly behavior of this heterotelechelic H-bonding polymer into supramolecular structures was explored, both in solution and in the bulk state. The first indication for the self-assembly of Ba−PnBuA−HW was obtained by ^{1}H NMR studies (Figure 2). When compared to the spectrum of Ba−PnBuA−RAFT, the emergence of HW protons and a considerable downfield shift of the barbiturate NH protons from 8.46 to 12.61 ppm were observed at the same concentration, strongly hinting on the formation of the expected specific H-bonded complex (Figure 2, top). Variable-temperature ^{1}H NMR studies demonstrated the thermoresponsive and reversible nature of the hydrogen bonds (Figure S7, Supporting Information).

Diffusion-ordered NMR spectroscopy (DOSY NMR) was subsequently employed to investigate the formation of supramolecular structures, as the differences in the size of self-assembled H-bonding polymers can reflect different diffusion coefficients (D_{NMR}) when compared to their precursor polymers.[38] Therefore, comparative DOSY NMR studies were carried out in toluene-d_8 at 27 °C, and D_{NMR} values of Ba−PnBuA−RAFT and Ba−PnBuA−HW at variable concentrations (0.15, 0.5, 2.0, 3.0, and 4.0 mM) were plotted as a function of the chemical shift. As seen in Figure 4, the measured average
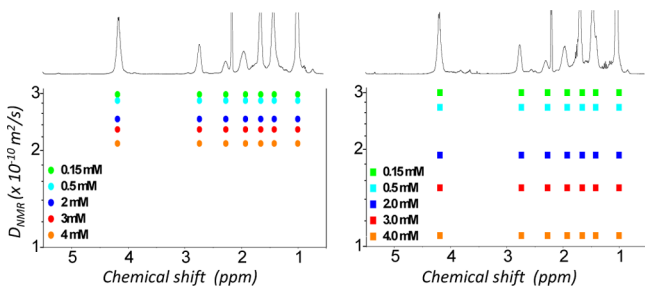

Figure 4. Concentration dependence of diffusion coefficient (D_{NMR}) distribution as a function of the chemical shift in toluene-d_8 at 27 °C. Left: Ba−PnBuA−RAFT. Right: Ba−PnBuA−HW.

D_{NMR} of Ba−PnBuA−RAFT (2.95 and 2.71 × 10^{-10} m^2/s) was comparable to the value of Ba−PnBuA−HW (3.01 and 2.85 × 10^{-10} m^2/s) at low concentrations (0.15 and 0.5 mM). However, upon increasing the concentration from 0.5 to 2 and 3 mM, a significant decrease of the diffusion coefficients (D_{NMR}) was observed in the case of Ba−PnBuA−HW (1.92 and 1.61 × 10^{-10} m^2/s, respectively) compared to Ba−PnBuA−RAFT (2.49 and 2.32 × 10^{-10} m^2/s, respectively). When the concentration was further increased to 4 mM, D_{NMR} was observed as 1.07 × 10^{-10} m^2/s in the case of Ba−PnBuA−HW. On the basis of this value, the hydrodynamic radius of the supramolecular structure generated from Ba−PnBuA−HW was subsequently estimated as 4.1 nm according to the Stokes−Einstein equation.[39,40] By contrast, D_{NMR} of Ba−PnBuA−RAFT was determined to be 2.11 × 10^{-10} m^2/s, corresponding to a hydrodynamic radius of 2.1 nm at 4 mM: this value is close to roughly half the size of the supramolecular structure (4.12 nm) from Ba−PnBuA−HW. Thus, the diffusion coefficients clearly demonstrated the formation of supramolecular structures driven by H-bonding with increasing concentration. Furthermore, based on the relationship between K_{ass} (∼10^5 M^{-1}) and

the virtual number of the associated polymer chains (DP$_n$),[41,42] the DP$_n$ of Ba−PnBuA−HW at 4 mM in toluene was deduced to be ∼20.

Further evidence of the successful formation of supramolecular structures via H-bonding was directly given by the visual appearance of resulting materials (Figure 5, inset). Ba−
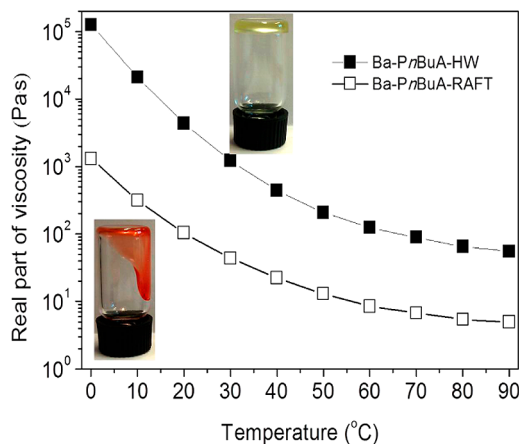
Figure 5. Melt viscosity versus temperature for Ba−PnBuA−RAFT and Ba−PnBuA−HW. Inset: resulting materials from Ba−PnBuA−RAFT (bottom) and Ba−PnBuA−HW (top) at room temperature.

PnBuA−HW displayed an entirely different rheological behavior compared to the precursor Ba−PnBuA−RAFT at room temperature: the transformation of Ba−PnBuA−RAFT to Ba−PnBuA−HW led to strongly changed viscoelastic properties of the resulting materials, showing a shift from a liquid like (Figure 5, inset bottom) to a solid like behavior (Figure 5, inset top).

Aiming at quantifying these viscoelastic properties, melt-rheological studies were subsequently carried out, investigating Ba−PnBuA−RAFT and Ba−PnBuA−HW by frequency-dependent measurements at different temperatures in the melt state. The real part of the viscosity was plotted as a function of temperature (Figure 5). Importantly, the supramolecular polymers self-assembled from Ba−PnBuA−HW in comparison to the precursor polymer Ba−PnBuA−RAFT that exhibited significant viscosity enhancements (by a factor of ∼97 at 0 °C), clearly indicating the generation of supramolecular structures by the heterotelechelic H-bonding polymer Ba−PnBuA−HW, further demonstrating that the properties of traditional homopolymers can be greatly promoted by incorporating H-bonding moieties.[29,43]

On the basis of the relationship between melt viscosity and molecular weight of (un)entangled linear polymers,[44] we first assumed that unentangled supramolecular polymers were generated (correctly omitting the formation of cyclic polymers at these high concentrations[35]): in this case a linear relationship between the molecular weight (M) and the viscosity (η) was assumed, calculating DP$_n$ as ∼90 (see Supporting Information for detailed calculations). Thus, the association number of the aggregated polymer is related to the melt viscosity of a comparable nonaggregating Ba−PnBuA−RAFT homopolymer,[45] containing the respective barbiturate moiety on one side but being devoid of the specifically aggregating HW moiety. In this calculation, ∼90 Ba−PnBuA−HW chains would be organized into a supramolecular linear chain. On the other hand, if the polymers were assumed to be in an entangled state

(thus the molecular weight M relates to the melt viscosity as $\sim\eta^{3.4}$), a DP_n equal to $\sim$4 would result under the same conditions (see Supporting Information for detailed calculations). Due to the possible supramolecular exchange between the supramolecular head groups, we propose an unentangled, rather than an entangled linear supramolecular polymer. Additionally, the shear modulus studies (Figure S8, Supporting Information) revealed higher storage (G') and loss (G'') moduli of Ba−PnBuA−HW in comparison to Ba−PnBuA−RAFT under the same conditions. Interestingly, decreasing the temperature to 10 and 0 °C led to the crossover of G' and G'' for Ba−PnBuA−HW when the scanning frequency was about 40 and 4 rad/s, respectively. As the small-angle X-ray scattering (SAXS) profile did not indicate the formation of clusters (Figure S9, Supporting Information) in the melt state, the formation of linear, nonclustered supramolecular polymers was assumed. Together with the results from solution and the good match between the DP_n (solution) and the DP_n (melt state) a similar linear aggregation mode can be concluded.

Overall, a straightforward route was exploited to achieve supramolecular polymers based on the heterotelechelic H-bonding polymer Ba−PnBuA−HW, designed via head-to-tail assembly driven by multiple H-bondings. The synthesis of the heterotelechelic polymer Ba−PnBuA−HW was realized by means of a RAFT process followed by aminolysis and a rapid, robust thio−bromo click reaction, completed at room temperature within 1 h. The complete macromolecular transformation of Ba−PnBuA−RAFT to Ba−PnBuA−HW was evidenced by the combination of ^{1}H NMR and MALDI-TOF mass spectrometry. The self-assembly behavior of the obtained heterotelechelic H-bonding polymer Ba−PnBuA−HW was subsequently investigated by temperature-dependent ^{1}H NMR, concentration-dependent DOSY NMR studies, and rheological measurements, proving the true formation of supramolecular polymers with an aggregated chain length of $\sim$90 (unentangled) or $\sim$4 (entangled) at 0 °C in the melt state and $\sim$20 units at 27 °C in toluene solution (4 mM). As part of our continuous study on the supramolecular polymer architectures, additional investigations in this direction are currently in progress and will be reported in due course.

ASSOCIATED CONTENT

Ⓢ Supporting Information

Details of synthesis, SEC trace, MALDI-TOF MS spectroscopy, temperature-dependent ^{1}H NMR studies, calculation of DP_n, shear modulus studies, and one-dimensional SAXS profile. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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