Supramolecular Chemistry

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Supramolecular ABC Triblock Copolymers**

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Herein we present a straightforward methodology for the synthesis of supramolecular ABC triblock copolymers. Supramolecular polymer chemistry is a major research focus as it has the potential to improve the versatility of polymeric materials through the incorporation of noncovalent interactions,[1,2] thereby generating dynamic and reversible, that is, "smart", materials.[3] Supramolecular functionalities can be incorporated into polymers in two distinct ways—by either side-chain[4,5] or main-chain functionalization.[6] The latter approach opens up new pathways for the preparation of block copolymers by using telechelic supramolecular polymers with different, sometimes incompatible, polymeric backbones,[7] and has the potential to yield materials with unprecedented and tunable properties.[8]

End functionalization of polymers with supramolecular moieties is typically carried out by post-polymerization functionalization.[9,10] This synthetic strategy, however, has two limitations: 1) the transformations are often nonquantitative and non-orthogonal to other functionalities along the polymer,[10] and 2) the introduction of two orthogonal and distinct supramolecular functionalities on two ends of a polymer is hard to imagine. Such unsymmetrically end-functionalized or heterotelechelic polymers[11] are important building blocks for supramolecular ABC triblock copolymers. Herein, we report the first synthesis of heterotelechelic polymers in a single step by using ring-opening metathesis polymerization (ROMP) as the key reaction. Our strategy affords straightforward incorporation of orthogonal recognition motifs at either chain end through the use of functionalized ruthenium initiators and chain terminators. We further demonstrate that a supramolecular ABC triblock copolymer can be obtained rapidly by simply mixing this heterotelechelic polymer with complementary telechelic polymers (Figure 1).

ROMP is the synthetic method of choice for our methodology since it is versatile, often living, and tolerant to a broad range of functionalities.[12] The use of functional chain terminators[13] or chain-transfer agents (CTAs)[14,15] affords mono- or symmetrical telechelic polymers in a one-pot procedure, which overcomes the limitation of the post-polymerization strategy as well as other controlled polymerization methods.[16]

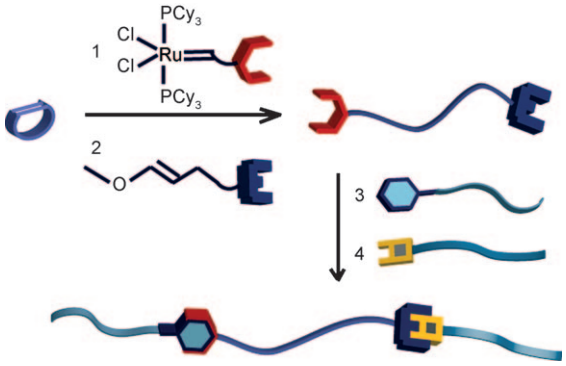

Figure 1. Schematic representation of the synthesis of a heterotelechelic polymer from functionalized initiators and chain terminators and its self-assembly to form supramolecular triblock copolymer.

Although functionalized ruthenium initiators[17] that bear basic functionalities for post-polymerization functionalization or masked functional groups are known, the introduction of molecular recognition units onto ruthenium initiators has not been reported to date. We rationalized that a styrene unit functionalized with such units can be used in a carbene exchange reaction to afford a ruthenium initiator functionalized with receptor moieties capable of noncovalent interactions. We further hypothesized that hydrogen-bonding moieties could be easily attached to a ruthenium initiator, since they are neutral towards the metal center. Thus, two hydrogen-bonding moieties, 2,6-diamido pyridine (DAP) and *N*,*N*′-bis[6-(alkanoylamino)pyridin-2-yl] isophthalamide (often referred to as the Hamilton receptor),[18] which exhibit weaker and stronger binding in nonpolar solvents, respectively,[5,19,20] were used for incorporation into the ROMP initiators.

Ruthenium initiators attached to either a DAP or the Hamilton receptor by a short spacer were synthesized by carbene exchange reactions by gently heating a mixture of the corresponding styrene and Grubbs' first-generation catalyst in dichloromethane at reflux. Analysis by using ^{1}H NMR spectroscopy showed that more than 85% conversion of the original complex to the functionalized initiator had occurred, as indicated by a shift of the carbene signals from $\delta = 20.0$ to 19.44 ppm in CD_2Cl_2. After purification by column chromatography, the DAP-substituted initiator **1** (Scheme 1) was obtained in 70% yield, whereas the Hamilton receptor functionalized initiator **2** was obtained in lower yield (25%) because of its decomposition on the silica gel column. The new initiators were characterized by NMR spectroscopy, mass spectrometry, and elemental analyses (see the Supporting Information).

Polymerization of norbornene octyl ester **3** (100% pure *exo* isomer) initiated by the new olefin metathesis initiators **1** or **2** proceeded rapidly. Complete initiations were observed

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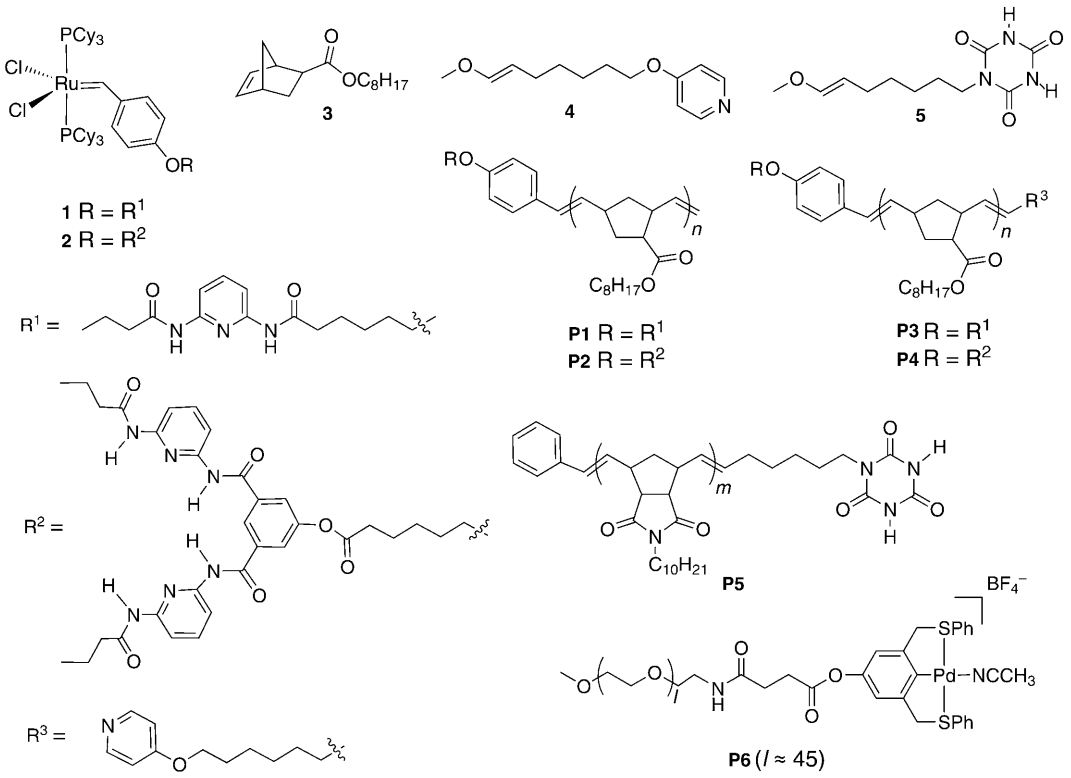

Scheme 1. Structures of functionalized initiators, chain terminators, and telechelic polymers used in this study.

by a shift of the carbene signal to $\delta = 18.5$ ppm in the ^{1}H NMR spectra. The propagation rate constants (K_p) were $1.9 \times 10^{-3}\,s^{-1}$ and $3.7 \times 10^{-3}\,s^{-1}$ for **1** and **2**, respectively; these values are slightly lower than that reported for the polymerization of *exo*-norbornene ester based monomers using Grubbs' first-generation catalyst.[21] The molecular weights of the polymers increased linearly with increasing monomer/initiator ratios. The living nature of the polymerization was further confirmed by the synthesis of block copolymers, the GPC traces of which were unimodal and showed complete shifts to high molecular weights. The new functionalized initiators are thus not only active towards ROMP of norbornenes but also afford living polymerizations.

The polymerizations were terminated by the addition of an excess of ethyl vinyl ether to afford monotelechelic polymers **P1** and **P2** (Table 1). To realize the synthesis of the targeted heterotelechelic poly(norbornene) polymers, a functionalized chain terminator (CT) is needed to terminate the ROMP that is initiated by a functionalized ruthenium complex, thereby installing the second functional group to the terminal end of the polymers. To incorporate a ligand for metal coordination at the other chain end of the polymer, pyridine-based CT **4** was employed. Complete termination of the ROMP of **3** initiated by **1** or **2** was observed after 3 h by the disappearance of the polymeric carbene signal in the ^{1}H NMR spectrum. Near-quantitative incorporation of both end-group functionalities in the polymer (**P3**, **P4**) was confirmed by ^{1}H NMR spectroscopy. Protons in the DAP moiety appear between $\delta = 7.6$–7.9 ppm, whereas those in the Hamilton receptor appear between $\delta = 7.4$–8.5 ppm in $CDCl_3$. The protons on the 1,4-disubstituted pyridyl ring could be seen at $\delta = 6.23$ and 7.28 ppm. These results demonstrate that the incorporation of recognition elements into ruthenium initiators opens new pathways for the synthesis of mono- as well as heterotelechelic polymeric materials.

Table 1: SEC data for telechelic polymers synthesized by ROMP.[a]

Polymer	M_w	M_n	PDI
P1	12200	7700	1.58
P2	9700	7100	1.37
P3	12100	7200	1.68
P4	11400	6800	1.66
P5	12600	9000	1.41

[a] Molecular weights were calculated against poly(styrene) standards with THF as eluant.

As a first step towards supramolecular ABC triblock copolymers, we studied the self-assembly of the terminal DAP and Hamilton receptors with the complementary small molecules *N*-hexylthymine and dibutylbarbiturate (DBB) by ^{1}H NMR titrations and isothermal titration calorimetry (ITC). We have utilized these receptors before in both main- and side-chain supramolecular polymers.[15,19] NMR titration curves were indicative of the weaker and stronger binding of DAP and Hamilton receptor moieties, respectively, although association constants (K_a) could not be calculated conclusively because of the lower concentration of the interacting moieties. The shape of the ITC binding isotherms for the interaction between the DAP moiety in **P1** or **P3** and *N*-hexylthymine was typical of a weak binding event ($K_a \approx 600\,M^{-1}$) and that for self-assembly of DBB with **P2** or **P4** (Figure 2a) was characteristic of a stronger binding event

($K_a = 3 \times 10^4\,M^{-1}$). The binding isotherms for the self-assembly of mono- and heterotelechelic polymers with complementary molecules were similar and the K_a values were the same within experimental error.

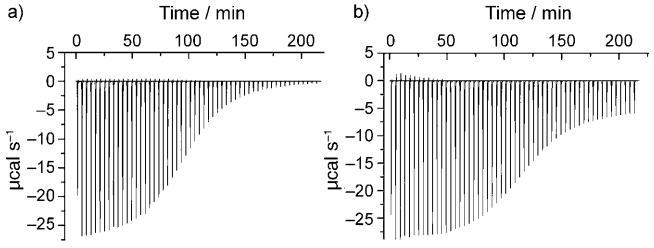

Figure 2. ITC binding isotherms for the self-assembly of a) **P4–DBB** and b) **P4–P5** in $CHCl_3$ at 30 °C.

For the formation of a supramolecular polymer, it is necessary that the noncovalent interactions are strong enough to hold the polymeric chains together. With the Hamilton receptor/barbiturate interaction displaying high association constants at one chain end and metal coordination at the other end, **P4** is a suitable candidate for the middle block in a supramolecular ABC triblock copolymer. We further envisaged that, as a proof-of-principle, all three blocks of an ABC triblock copolymer should consist of different polymeric backbones. Therefore, a cyanuric acid terminated poly(norbornene imide) (**P5**) was synthesized by ROMP termination of the corresponding monomer with CT **5**, while a carboxylic acid terminated PEO was functionalized with a Pd pincer coordinated to an acetonitrile ligand to give **P6**.

To confirm that metal coordination does not affect the hydrogen-bonded complex in the telechelic polymers, as we have shown in side-chain functionalized polymers,[22] a small-molecule analogue of **P6** (**6**) was added to **P4**, which itself was hydrogen bonded to DBB. The ^{1}H NMR spectrum of the complex revealed that the pyridyl protons (both α and β), shifted downfield from $\delta = 7.26$ and 6.26 ppm to $\delta = 7.40$ and 6.45 ppm, respectively. Integration of the signals for the β protons confirmed quantitative metal coordination. The chemical shifts of the amide protons in the Hamilton receptor were unchanged, which indicates that metal coordination did not interfere with the hydrogen-bonded complex. Both our and other research groups have also shown that pyridyl groups can replace acetonitrile ligands in metal–pincer complexes by simply mixing the two components, which leads to stable polymeric assemblies.[23,24] Thus, from these preliminary studies, preparation of ABC triblock copolymers seemed feasible.

The formation of an AB diblock copolymer (PAB) by hydrogen bonding was initially studied. Addition of one equivalent of **P5** to **P4** revealed complete shifts of the amide protons (labeled a and b in Figure 3) of the Hamilton receptor to $\delta = 9.5$ and 9.95 ppm (labeled a′ and b′) in the ^{1}H NMR spectra (Figure 3b). The ITC binding isotherm for the **P4–P5** interaction (Figure 2b) was similar to that for the **P4**–DBB interaction (Figure 2a), however, a somewhat weaker interaction, probably arising from entropic factors, was determined. The association constant (K_a) for the **P4–P5** interaction was found to be $1.2 \times 10^4\,M^{-1}$, which is comparable to that found in other telechelic polymers functionalized with Hamilton receptors.[2] PAB is a monotelechelic diblock copolymer and can be potentially functionalized at the pyridyl end through metal coordination. This possibility was tested by adding **6** to PAB. A shift in the signals for the pyridyl protons in the ^{1}H NMR spectrum, which is indicative of quantitative metal coordination,[24] was observed; this observation suggests that PAB can indeed be functionalized by metal coordination.

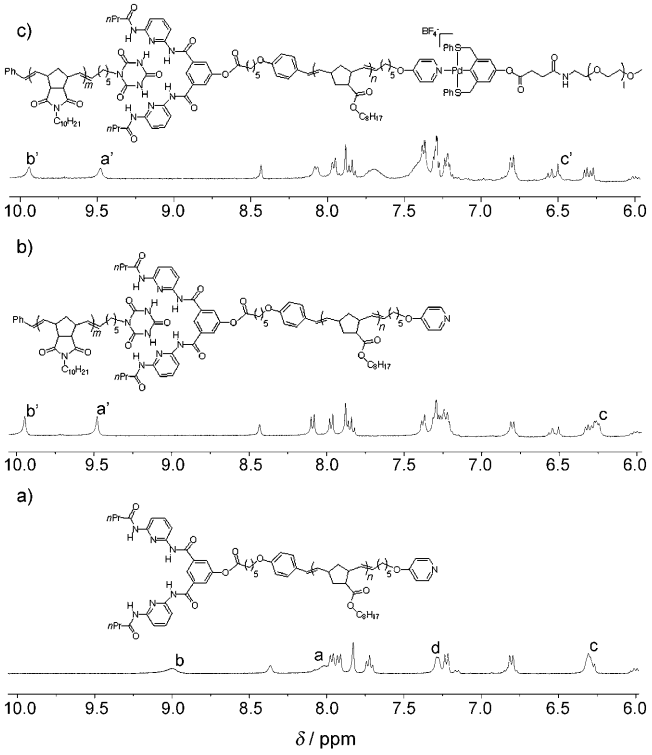

Figure 3. ^{1}H NMR spectra of a) **P4**, b) **PAB**, and c) **PABC** in CD_2Cl_2.

To achieve the formation of the target supramolecular triblock copolymer, **P6** was added to PAB. Again, complete shifts of the β-pyridyl protons (from c to c′) indicated quantitative self-assembly of the PEO block to PAB by metal coordination. The signals for the amide protons were unaffected, which suggests the orthogonality of both interactions and the formation of a supramolecular ABC triblock copolymer, PABC. Although the signals for pyridyl protons (c and d) broaden and overlap with other peaks, studies with small molecules provide supportive evidence for this recognition event. Additional confirmation for this polymeric self-assembly by ITC could not be obtained however, since the binding strength of metal coordination exceeds the limit of this technique.

Solution viscosity studies were carried out to characterize the polymer formation in more detail. Supramolecular block copolymers PAB and PABC are high-molecular-weight species compared to their individual blocks and therefore should possess higher solution viscosities. The specific viscosity (η_{sp}) of PAB and PABC and precursor telechelic

polymers **P4** and **P5** were measured using a semimicro Ubbelhode viscometer in CH_2Cl_2 at 25 °C. The plot of η_{sp} versus concentration for these polymers is shown in Figure 4.

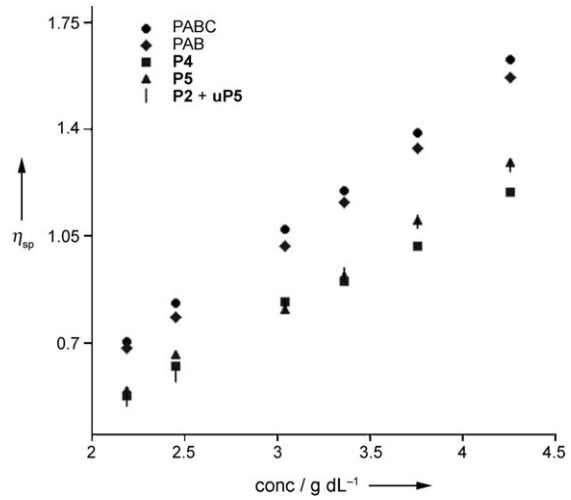

Figure 4. Plot of specific viscosity versus concentration for block copolymers and homopolymers.

Clearly, PABC has the highest specific viscosity, with only slightly lower viscosities exhibited by PAB. This is understandable because the molecular weight difference in these two polymers is only about 2.6 kD, which is that of **P6**. The precursor homopolymers **P4** and **P5**, however, have notably lower η_{sp} values. In a control experiment, the specific viscosity of a mixture of **P2** and unfunctionalized analogue of **P5** was found to be nearly the same as that of **P4** and **P5**. Thus, the viscosity data augments the NMR and ITC data to strongly suggest the formation of a supramolecular ABC triblock copolymer.

In summary, we have developed a methodology based on olefin metathesis for the synthesis of heterotelechelic polymers that bear two different binding motifs at their chain ends. The key breakthrough for this methodology was the design and synthesis of ruthenium initiators functionalized with recognition units. We have also demonstrated the assembly of supramolecular ABC triblock copolymers, the central block of which is a heterotelechelic polymer self-assembled with complementary recognition-unit-functionalized telechelic polymers.

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