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Polymer Architectures

Rotaxane-Based Mechanically Linked Block Copolymers**

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Block copolymers constitute an extremely important class of materials because of their utility in countless applications.[1] The development of controlled polymerization methods and the combined use of polymer and organic chemistries have enabled the production of complex architectures and highly functional polymers.[2] Recently, block copolymers that bear an addressable junction have attracted particular interest because of the added functionality and additional degrees of control of the properties and the self-assembly behavior of such copolymers.[3–8] Two main types of junction have been reported to date: 1) supramolecular junctions based on, for example, hydrogen bonds, metal–ligand coordination, or inclusion or host–guest complexes,[3–5] and 2) covalent junctions that are responsive to various kinds of stimuli (light, pH, or redox).[6–8] Herein we report the synthesis of a diblock copolymer where the two blocks are linked by a new type of junction: a mechanical bond of the rotaxane type (**1** and Figure 1).

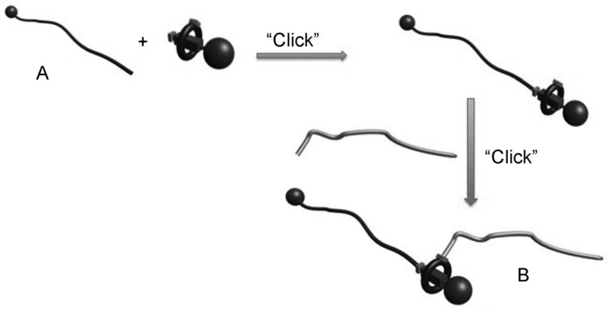

Figure 1. Convergent synthetic strategy toward A-*rot*-B block copolymers.

Interlocked molecules such as catenanes and rotaxanes have attracted ever-increasing interest since the discovery in the late 1980s and early 1990s of efficient synthetic methods to prepare these molecules. This interest stems largely from the unique degrees of freedom associated with the mechanical (or topological) bond, that is, it allows for large-amplitude controlled motions of the interlocked components, and for their relative positioning with respect to each other. These exceptional properties have made catenanes and rotaxanes highly promising candidates for the design of molecular machines that are capable of performing well-defined tasks in response to various stimuli.[9] Moreover, these molecules also show great potential for imparting unusual properties to polymers.[10] Indeed, the unique flexibility and mobility of catenanes and rotaxanes, and their incorporation into polymers is expected to strongly modify the rheological, mechanical, dynamic, and thermal properties of the polymers. This promise of polymeric materials exhibiting new properties has thus generated an intense activity of research that has led to the creation of polycatenanes and polyrotaxanes of diverse compositions and architectures.[10] In all these examples, the topological bonds were incorporated into the repeating units (in the main chain or as side groups) of the polymers. Contrary to these examples, here we use a single mechanical bond of the rotaxane type that is strategically located at the junction between two polymer blocks (see Figure 1), thus giving rise to a new kind of diblock copolymers designated as A-*rot*-B. In this way, the blocks are linked by a bond that has the strength of a covalent bond, since the two interlocked components cannot be separated unless a covalent bond is broken, but which confers unique degrees of freedom to the polymer chains since the macrocycle that bears the B block can potentially move along the whole length of the A block that acts as the thread. Copolymers of this type would thus enable motions of much larger amplitude than with conventional "small" rotaxanes, and constitute a first step toward large, fully synthetic, systems that mimic biological structures, where large-amplitude motions are commonplaces.[11]

The chosen synthetic strategy is depicted in Figure 1. Among the different possible routes, we selected one that shows a highly convergent character, and where the key step (the rotaxanation) is performed on a "small" molecule and not on a polymer chain end. As a template for the pseudorotaxane formation, we selected a square-planar Pd^{II} complex built from one tridendate and one monodendate ligand. This very efficient template has been successfully used for the preparation of various catenanes[12] and rotaxanes.[13] Moreover, the template is a neutral complex that can be used in a variety of organic solvents, and is robust enough to withstand chemical modifications performed on other parts of the molecule. Once available, the different building blocks can be assembled by two successive copper(I)-catalyzed azide–alkyne cycloaddition (CuAAC) "click" reactions to produce the A-*rot*-B diblock copolymer.[14] By following this strategy, a higher degree of control on the formation of the topological bond will be achieved, and its convergent nature

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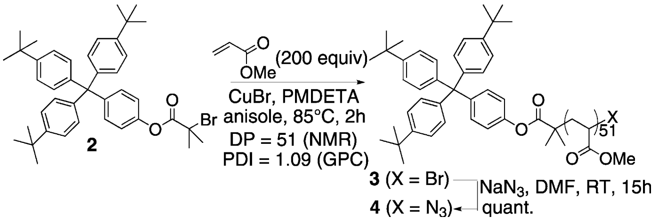
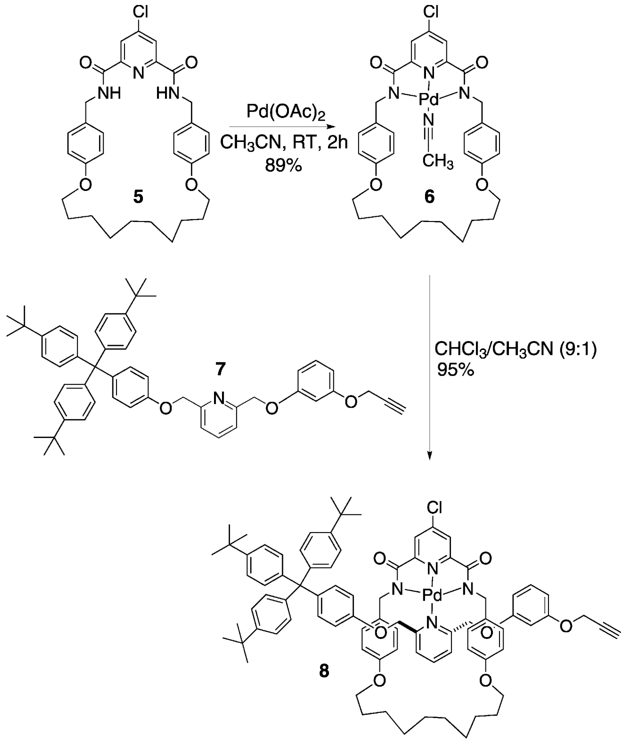
allows an easy variation of the chemical structure of the polymer chains.

The first building block is the polymeric thread **4**, which is end-capped by a bulky stopper at one end, and by an azide moiety at the other. We synthesized the atom transfer radical polymerization (ATRP) initiator **2** that bears the bulky stopper (easily prepared from the corresponding phenol, see the Supporting Information). This procedure allows the facile synthesis of threads of different length and/or chemical nature without having to graft the bulky stopper in a subsequent step. As an example, we chose to polymerize methyl acrylate. The ATRP polymerization of methyl acrylate from initiator **2** was performed in anisole with an equimolar CuBr/pentamethyldiethylenetriamine (PMDETA) complex as catalyst. A well-defined poly(methyl acrylate) (PMA) with a polydispersity index (PDI) of 1.09 and M_n of 5040 g mol^{-1}, and bearing a bulky stopper at one of its extremities (**3**) was obtained in this way. Characterization by MALDI mass spectrometry confirmed the presence of the expected end groups (see the Supporting Information). The bromide chain end was then substituted with NaN_3 to quantitatively produce the azide-terminated polymeric thread **4** (Scheme 1).



Scheme 1. Synthesis of the polymeric thread **3** by ATRP from an initiator that bears a bulky stopper.

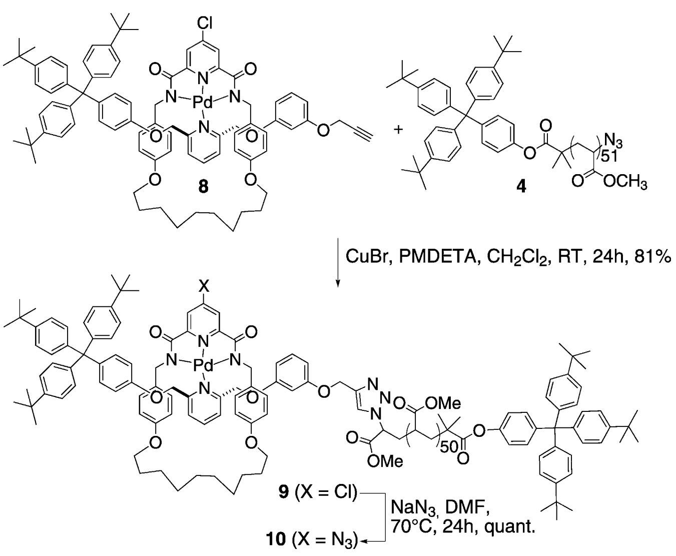
The next step was to prepare the pseudorotaxane **8**, which bears the second bulky stopper and an alkyne group, in order to enable attachment of **8** to the polymer thread **4**. We selected a square-planar complex centered on a Pd^{II} ion as a template for the pseudorotaxane. In order to efficiently template the rotaxane formation, this complex has to be built from both a tridendate ligand, which is first complexed with the Pd^{II} ion, and from a monodendate ligand.[12,13] In our case, the tridendate ligand is the 2,6-pyridinedicarboxamide motif of the macrocycle **5**, and the monodendate ligand is the pyridine station present on the small thread **7** (Scheme 2). The pseudorotaxane **8** is then assembled by threading compound **7** through the cavity of macrocycle **6**; the pyridine station displaces the acetonitrile molecule present in **6**. The structure of the small thread **7** is inspired by previous studies[13a,b,f] that showed that 1) the presence of a bulky group on one side of the pyridine station, 2) the presence of a rigid arm (here the resorcinol fragment) on the other side of the pyridine station, and 3) the 2,6-substitution of the pyridine ring all favor threading the macrocycle through the cavity and minimize the chance of an *exo* complexation, that is, the noninterlocked configuration. The small thread **7** was obtained in good yield in three steps starting from 2,6-bis(chloromethyl)pyridine and from the phenol form of the bulky stopper (see the Supporting Information). The palladium-complexed macrocycle **6** was obtained by adapting a previously reported procedure that uses chelidamic acid as starting material.[13a] The pseudorotaxane **8** was formed in good yield by simply mixing the small thread **7** and the macrocycle **6** at room temperature for 1 hour (Scheme 2), as unambiguously shown by ^1H NMR spectroscopy and mass spectrometry (see the Supporting Information).



Scheme 2. Synthesis of pseudorotaxane **8** by slipping thread **7** through the cavity of the palladium-complexed macrocycle **6**.

With the building blocks available, the assembly of the A-*rot*-B copolymer could be performed. The first step is the attachment of the pseudorotaxane **8** onto the chain end of the polymeric thread **4** by the CuAAC reaction to obtain the macrorotaxane **9** (Scheme 3). This reaction was performed at room temperature with CuBr/PMDETA as catalyst. As shown by the mass spectrum of **9** (Figure 2), the clear mass shift to higher values than those of thread **4** and the very good agreement between experimental and isotope distributions confirm the efficiency of the coupling reaction. The Cl group present on the macrocycle was then substituted by an azide moiety by reacting the macrorotaxane **9** with NaN_3. Aromatic substitution of the Cl by the azide group occurs smoothly in this case because of the presence of the two amide groups on the aromatic cycle and the complexation of the pyridine nitrogen atom with the palladium center.

The final step toward the A-*rot*-B copolymer is the attachment of the B block onto the macrocycle of the macrorotaxane **10** by the CuAAC reaction. As B block we selected a poly(ethylene oxide) (PEO) chain (M_n = 2000 g mol^{-1}, PDI = 1.05) end-capped with a propargyl group to allow its reaction with the azide group on the macrocycle. The CuAAC reaction was conducted in chloro-



Scheme 3. Synthesis of the macrorotaxane **10** by attaching the pseudorotaxane **8** onto the chain end of the polymeric thread **4**.

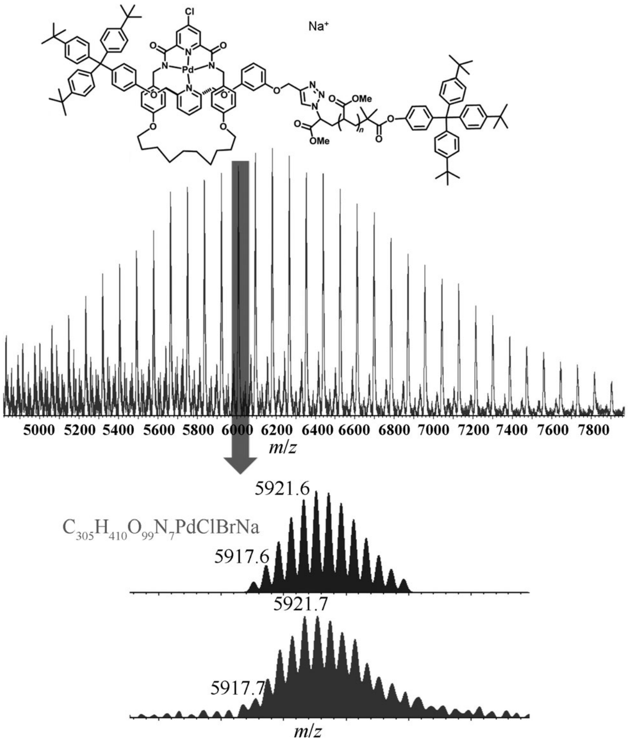
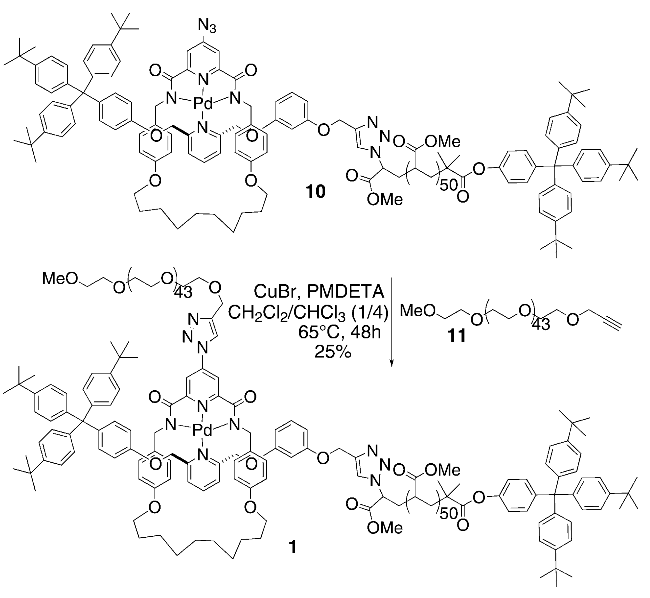


Figure 2. MALDI mass spectrum of macrorotaxane **9**. The expansion shows the very good agreement between the experimental (lower) and theoretical isotope distributions (upper).

form heated at reflux with the CuBr/PMDETA complex as catalyst. After purification to remove the residual homopolymers, the PMA-*rot*-PEO copolymer was obtained in a satisfactory yield, when considering the complexity of the system (Scheme 4).

Figure 3 shows a comparison of the size-exclusion chromatography (SEC) traces of the polymeric thread **3**, of the macrorotaxane **9**, and of the PMA-*rot*-PEO copolymer **1**. A shift toward shorter elution times is clearly visible between each of the three compounds, thus confirming the increase in molecular weight at each step of the assembly of the copolymer. Moreover, the ^{1}H NMR spectrum of copolymer **1** (see the Supporting Information) confirms its structure since the integrated areas under the PMA and PEO signals match the expected composition of the copolymer.



Scheme 4. Last step of the assembly of the PMA-*rot*-PEO copolymer by attaching the PEO chain **11** onto the macrocycle of macro-rotaxane **10**.

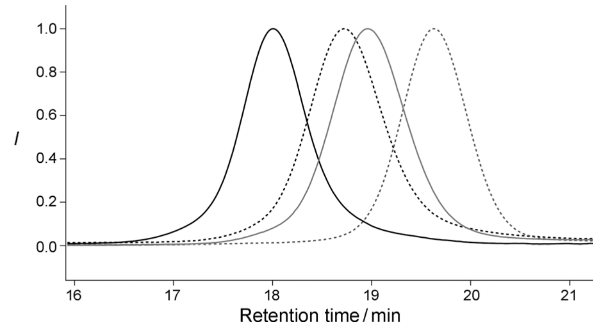


Figure 3. SEC traces of the building blocks **3** (solid gray line), **9** (dashed black line), **11** (dashed gray line) and of the PMA-*rot*-PEO copolymer **1** (solid black line). (Eluent: DMF, flow rate: 1 mL min^{-1}, refractive index detector, normalized intensities are shown.)

To obtain further evidence for the obtained structure, the PMA-*rot*-PEO copolymer **1** was analyzed by MALDI mass spectrometry. As shown in Figure 4, the resolution of the MALDI mass spectrum obtained for copolymer **1** is significantly lower that of the macrorotaxane **9**. Since compound **1** is a copolymer of PEO and PMA, the low mass difference between EO and MA units ($2\times\text{EO}=88$ Da and $\text{MA}=86$ Da) leads to many isobaric ions, thus explaining the lower resolution. Nevertheless, an interesting global shift with an *m*/*z* difference of 2000 is observed, thus confirming the grafting of the PEO chain ($M_n = 2000\ \text{g mol}^{-1}$) onto the

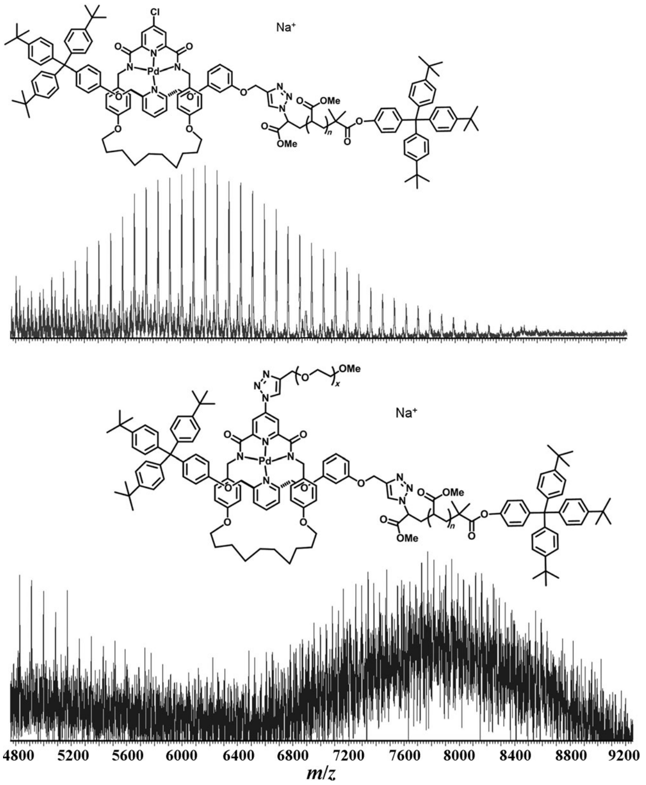


Figure 4. Comparison of the recorded MALDI mass spectra before and after attachement of the PEO block to the macrorotaxane. In the bottom spectrum, signals with low *m/z* ratios correspond to PMA-containing fragment ions produced by decomposition of the copolymer (higher laser fluence conditions).

macrorotaxane and therefore the structure of the PMA-*rot*-PEO copolymer **1**.

In conclusion, we have described the first synthesis of an original diblock copolymer where the two blocks are linked by a mechanical bond of the rotaxane type. The proposed strategy, by virtue of its modular and convergent character, will allow the preparation of a series of copolymers with tunable composition. Moreover, it offers several possibilities of adaptation, for example by replacing the second CuAAC reaction by a polymerization step that uses a modified macrorotaxane as macroinitiator. This modification would further broaden the accessible composition range and could give access to copolymers with high molecular weights. The type of copolymers reported here opens promising pathways to study the sliding motion of a macrocycle along a polymer chain. Gaining insight in such mechanisms is indeed very important for the development of synthetic molecular machines, for example, systems that mimic processive enzymes.[15]

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