JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Communication

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Rare Earth Metal-Mediated Group-Transfer Polymerization: From Defined Polymer Microstructures to High-Precision Nano-Scaled Objects

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Supporting Information

ABSTRACT: Poly(2-isopropenyl-2-oxazoline) (PIPOx) and poly(2-vinylpyridine) (P2VP) have been efficiently synthesized using bis(cyclopentadienyl)methylytterbium (Cp_2YbMe) as catalyst. The polymerizations of 2-isopropenyl-2-oxazoline (IPOx) and 2-vinylpyridine (2VP) follow a living group-transfer polymerization (GTP) mechanism, allowing a precise molecular-weight control of both polymers with very narrow molecular-weight distribution. The GTP of IPOx and 2VP occurs via N coordination at the rare earth metal center, which has rarely been reported previously. The relative coordination strength of different monomers at the ytterbium center is determined by copolymerization investigations to be in the order of DEVP > MMA > IPOx > 2VP. In combination with living cationic ring-opening polymerization, PIPOx is converted to molecular brushes with defined backbone and poly(2-oxazoline) side chains using the *grafting-from* method.

Since the first report on rare earth metal-mediated group-transfer polymerization (REM-GTP) by Yasuda et al. in 1992,[1] researchers have devoted their efforts to optimizing reaction conditions and initiator efficiency and extending its utilization for various monomers, e.g., (meth)acrylates and (meth)acrylamides.[2−4] In view of the mechanism, this type of polymerization is recognized as coordinative anionic, and due to its similarity to silyl ketene acetal-initiated GTP, it is also referred to as transition metal-mediated GTP.[4−12] Because of its highly living character, REM-GTP leads to strictly linear polymers with very narrow molecular-weight distribution (Đ < 1.1), exhibits a linear increase of the average molar mass upon monomer conversion, and allows the synthesis of block copolymers as well as the introduction of chain end functionalities.[2−4,11] Coordination of the growing chain end at the catalyst suppresses side reactions and allows stereospecific polymerization as well as activity optimization by varying both the metal center and the catalyst ligand sphere.[4,11] Accordingly, REM-GTP combines the advantages of living ionic and coordinative polymerizations and thus allows a precise adjustment of the polymer architecture and microstructure.

Recently, our group and other researchers showed that REM-GTP is not restricted to common (meth)acrylates but is also applicable to several other monomer classes of interest, e.g., vinylphosphonates and vinylpyridines.[6−8,11,13,14] Moreover, we reported on the development of a surface-initiated group-transfer polymerization (SI-GTP) mediated by rare earth metal catalysts, allowing the perfect decoration of substrates with polymer brushes of specific functionality.[15] Inspired by these recent advances and the high precision offered by REM-GTP, we have made it a major focus of our research to extend the applicability of this method to further monomer classes and to evaluate the utilization of REM-GTP for the production of tailor-made functional polymer-based architectures. In this context, this Communication describes the efficient polymerization of 2-isopropenyl-2-oxazoline (IPOx) and 2-vinylpyridine (2VP) through REM-GTP, occurring via N coordination of the monomer at the rare earth metal center. Copolymerization experiments are conducted to compare the coordination strength of the different monomers to the rare earth metal. Moreover, REM-GTP is combined with living cationic ring-opening polymerization (LCROP), giving the first access to poly(2-oxazoline) molecular brushes with narrow side chain and backbone chain length distribution.

IPOx is a versatile dual-functional monomer comprising an oxazoline and a vinyl moiety. On one hand, it can undergo LCROP of the heterocyclic motif, resulting in defined poly(2-oxazoline)s for a variety of applications in biomedicine.[16−24] On the other hand, radical/anionic polymerization of the vinylidene functionality of IPOx leads to poly(2-isopropenyl-2-oxazoline) (PIPOx) with a broad molecular-weight distribution,[16,25] even though anionic and reversible addition−fragmentation polymerization finitely improves the distribution character.[26,27] Living anionic polymerization, owing to the strict operating conditions and solvent effects,[28] is not a preferred method for the polymerization of IPOx. Moreover, due to a strong complexation of pendant 2-oxazoline units by copper, attempts to polymerize IPOx by atom-transfer radical polymerization (ATRP) were not successful.[25] There seems to be no truly successful method by which PIPOx with controlled molecular weight and narrow Đ (Đ < 1.1) is accessible. Also for 2VP, another functional monomer comprising a C═C—C═N functionality, there is a continuing demand to seek superior methods for efficient and convenient polymerization. Inspired by the electronic and structural similarity between IPOx/2VP and (meth)acrylates or vinylphosphonates, as well as initial investigations on rare earth metal-

Received: April 11, 2013
Published: June 4, 2013

dx.doi.org/10.1021/ja4036175 | J. Am. Chem. Soc. 2013, 135, 8810−8813

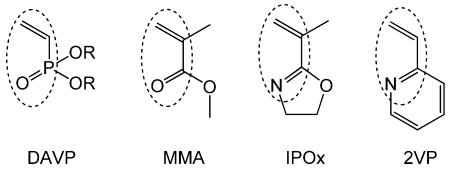

Figure 1. Molecular structures of dialkyl vinylphosphonates (DAVP), methyl methacrylate (MMA), 2-isopropenyl-2-oxazoline (IPOx), and 2-vinylpyridine (2VP).

mediated 2VP polymerization,[13] we examined the polymerizability of IPOx/2VP employing rare earth metal complexes as catalysts (Figure 1).

Initially, the polymerization of IPOx was conducted at room temperature in the presence of Cp_2YbCl and Cp_3Yb. In contrast to using MMA and vinylphosphonates,[4,11,29] no polymerization was observed using Cp_2YbCl as initiator. This was attributed to the rather weak coordination strength (*vide infra*) of IPOx at the metal center, inhibiting cleavage of the dimeric complex $[Cp_2YbCl]_2$. This hypothesis could be confirmed by X-ray structure analysis of single crystals obtained from a mixture of IPOx and Cp_2YbCl in toluene, which were found to be the $[Cp_2YbCl]_2$ starting material. Using Cp_3Yb as catalyst, low yields of polymer could be isolated after several hours of polymerization at room temperature. The poor efficiency of Cp_3Yb for IPOx in contrast to its high reactivity for DEVP polymerization under identical reaction conditions is attributed to the lower steric crowding of the intermediate Cp_3Yb(IPOx) in comparison to Cp_3Yb(DEVP), leading to an inefficient initiation of IPOx REM-GTP by Cp_3Yb.[7]

Using Cp_2YbMe as initiator, polymerization of IPOx proceeded smoothly at room temperature, exhibiting high reaction velocity; i.e., monomer conversion reached 95% within 2 h at room temperature, as monitored by *in situ* ^{1}H NMR (Figure 2). According to MMA, the methyl group was found to be an efficient initiator for IPOx polymerization (Table 1).[4] This

Table 1. Summary of Different Polymerization of IPOx (Monomer:Initiator = 200:1)

initiator	T (°C)	TOF[a,b] (h^{-1})	PDI[c]	M_n[c] (kDa)	I*[d] (%)	reaction time (h)/ conversion[b] (%)
Cp_3Yb	25	—	—	—	—	10/trace
Cp_2YbMe	25	380	1.04	21	95	1.5/92
BuLi	25	3100	1.5	40	53	0.2/95
BuLi	−78	18	1.2	2.5	—	2/18
AIBN	60	—	2.0	18	—	8/59

[a]The turnover frequency (TOF) was defined as the maximum slope of the conversion vs reaction time plot. [b]Determined by ^{1}H NMR. [c]Determined by GPC-MALS. [d]I* = M_{th}/M_n, M_{th} = 200M_{Mon} × conversion + $M_{end\ group}$.

is attributed to the absence of an acidic α-CH, as Cp_2YbMe was found to yield a rather inefficient initiation by deprotonation for vinylphosphonate REM-GTP.[29] The obtained PIPOx was characterized by ^{1}H NMR (Figure 2). After REM-GTP, the IPOx vinylene proton signals (5.76 and 5.39 ppm) disappear completely, and new peaks at 1.76−2.13 ppm originating from protons of formed methylene groups arise. The 2-oxazoline ring was well preserved after polymerization, as can be seen from ^{1}H NMR, with chemical shifts of the oxazoline ring protons slightly shifted from 3.92 and 4.26 ppm to 3.76 and 4.16 ppm, respectively. ^{1}H and ^{13}C NMR spectroscopic analysis (Figure

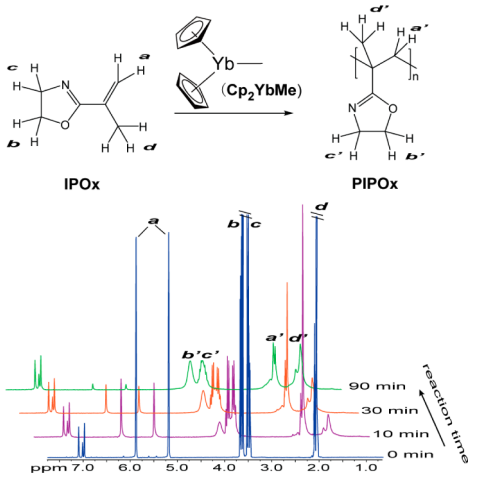

Figure 2. Reaction scheme for GTP of IPOx and polymerization kinetics as detected by *in situ* ^{1}H NMR and assignment of corresponding signals.

S2) indicates the produced PIPOx to be atactic ([mr] = 35%), which can be attributed to the rather small steric demand of the Cp ligands, which is insufficient to induce a stereospecific polymerization.

To elucidate the underlying initiation process, oligomers were produced by using an IPOx:Cp_2YbMe ratio of 5:1 in toluene and subsequently analyzed by electrospray ionization mass spectrometry (ESI-MS). For all peaks, the molar mass of the corresponding oligomers was found to be $n \times M_{IPOx} + 17$ or $n \times M_{IPOx} + 39$ g/mol (see Figure 4b and Table S1). The remaining 17 or 39 g/mol corresponds to a methyl group, which initiated chain growth, a H^+ (or Na^+), and a proton from the termination reaction during methanolic workup. Therefore, transfer of a coordinated ligand (CH_3) to a monomer in the initial step is evident. According to MMA, REM-GTP of IPOx is believed to proceed via an eight-membered ring chelate as shown in Figure 3a, with chain growth occurring by conjugate addition of a coordinated monomer to the covalently bound chain end.[4,11] Attempts to isolate IPOx adducts or the eight-membered intermediate by mixing IPOx and Cp_2YbMe in 1:1 and 2:1

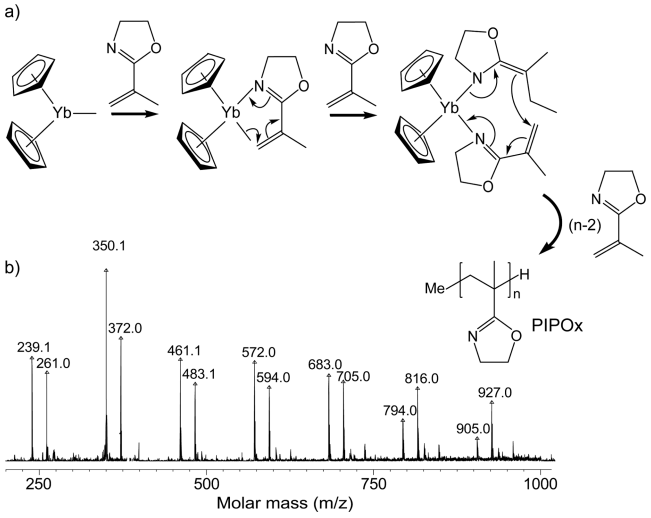

Figure 3. (a) Schematic illustration of REM-GTP of IPOx concerning initiation and propagation. (b) Structure of 2-isopropenyl-2-oxazoline oligomer and its ESI-MS spectrum.

dx.doi.org/10.1021/ja4036175 | *J. Am. Chem. Soc.* 2013, 135, 8810−8813

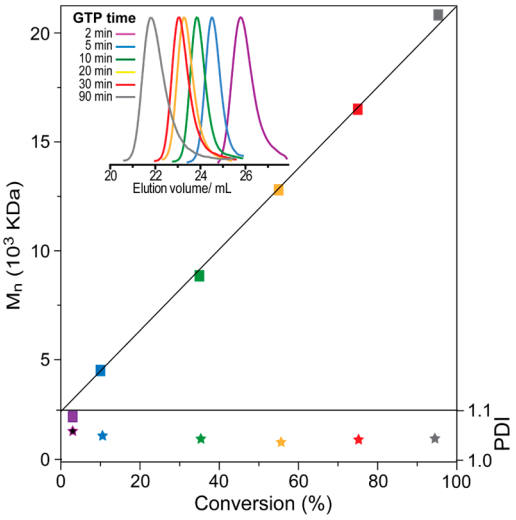

Figure 4. Linear growth of the absolute molecular weight (M_n) determined by multi-angle laser light scattering as a function of IPOx conversion (determined by ^{1}H NMR). Inset: GPC traces as detected by retention volume.

molar ratios at room temperature and −35 °C were unsuccessful, consistently yielding oligomeric PIPOx. However, according to previous literature on rare earth metal oxazoline complexes[30,31] and rare earth metal-mediated 2VP polymerization,[13] we presume the coordination of the eight-membered intermediate as well as the monomer to proceed via the N atom of the oxazoline moiety, thus providing one of the first examples of REM-GTP to proceed via N coordination at the metal center.

To further examine the character of the established REM-GTP of IPOx, aliquots were taken at regular time intervals during the polymerization and analyzed by gel permeation chromatography multi-angle light scattering (GPC-MALS) to estimate the absolute number-averaged molar mass (M_n) and the polydispersity index (PDI) of PIPOx. A plot of the M_n (from 2.05×10^3 to 2.10×10^4 g/mol) vs monomer (IPOx) conversion (from 2.1% to 95%, respectively) reveals a linear relationship between these two parameters (Figure 4), whereas the PDI remains extremely narrow (PDI < 1.07) for polymers obtained at all conversions. The linear growth of molecular weight against monomer conversion is ascribed to the highly living character of REM-GTP and the observed high initiator efficiency (I^* = 95%).

In order to demonstrate the superiority of REM-GTP in comparison to other polymerization techniques, the polymerization of IPOx initiated by azobisisobutyronitrile (AIBN) and *n*-butyllithium (BuLi) at different temperatures was investigated. As expected, free radical polymerization of IPOx performed at 60 °C afforded PIPOx with broad polydispersity (PDI = 2.0, conversion = 59%). Living anionic polymerization of IPOx at −78 °C for 2 h yielded a polymer with improved molar mass distribution (PDI = 1.2) but slow polymer chain growth rate (M_n = 2.5 kDa after 2 h polymerization, conversion = 18%). Anionic polymerization of IPOx at room temperature largely increased the polymerization velocity, however, at the cost of side reactions and loss of control. As a result, the PDI of the obtained polymer increased significantly (PDI = 1.5). The polymerization results for different methods and the used reaction conditions are summarized in Table 1.

In order to verify the versatility of REM-GTP for other monomers, which coordinate to the metal center via an N atom, we subjected another structural similar monomer, i.e. 2VP, to the REM-GTP reaction conditions. To our delight, the GTP of 2VP occurred and afforded poly(2-vinylpyridine) (P2VP, 43 kDa) in 24 h at room temperature. We found the activity and the initiator efficiency of 2VP REM-GTP to be much lower (TOF = 44 h^{-1}, I^* = 45%) (Figure S4) than those for IPOx (TOF = 380 h^{-1}, I^* = 95%) (Figure S1), which may be attributed to the electron delocalization and thus the weak N−Yb coordination. Nevertheless, the PDI of obtained P2VP was narrow (PDI = 1.1) at all monomer conversions (Figure S6). Hence, we attribute the low initiator efficiency to an initial catalyst deactivation by impurities. It was recently shown by Mashima et al. that end-functionalized P2VP could be efficiently obtained by yttrium complex-catalyzed polymerization.[13] Albeit our simple ytterbium complex exhibits relatively lower activity in the polymerization of 2VP, the catalyst led to high molar mass P2VP. Therefore, further investigation on the optimization of the catalyst is necessary. It is worth mentioning that ESI-MS investigation of oligomeric P2VP indicates the initiation to occur via a methyl transfer (Figure S5), even though an α-CH is present in 2VP. According to the small steric demand of the Cp ligands, as expected, produced P2VP is atactic as indicated from ^{1}H and ^{13}C NMR analysis (Figure S3).

In REM-GTP copolymerizations, the addition sequence of the comonomers is critical for monomers with different coordination strength to the metal center; i.e., monomers can only be polymerized in order of increasing coordination strength.[6,11,32] In order to examine the relative coordination strength of the newly employed N-coordinating monomers IPOx and 2VP, statistical copolymerizations using DEVP, MMA, IPOx, and 2VP were conducted. Consistently, only the corresponding homopolymers of the stronger coordinating comonomer were obtained, as observed via NMR spectroscopy, revealing a monomer coordination strength to the ytterbium center in an order of DEVP > MMA > IPOx > 2VP. Accordingly, sequential copolymerization yielded diblock copolymers in sequences of PMMA-*b*-PDEVP, PIPOx-*b*-PMMA, and PIPOx-*b*-PDEVP, as well as P2VP-*b*-PIPOx and P2VP-*b*-PDEVP, while diblock copolymerization in the reverse sequence only afforded homopolymers of PDEVP, PMMA, and PIPOx, respectively (Table S1). However, diblock copolymer synthesis was found to be hindered by a proposed encapsulation of the catalyst during polymerization of the rather hydrophilic IPOx and 2VP. This hypothesis is underlined by precipitation of formed high-molecular-weight PIPOx and P2VP from toluene solution and by ineffective initiation of a second, more hydrophobic comonomer (e.g., MMA) by the PIPOx or P2VP macroinitiator. Moreover, if the degree of polymerization of the first, hydrophilic block is kept low (below 20), an improvement of the PIPOx macroinitiator efficiency could be observed. Chain termination is not a major limitation, as the formation of block copolymers for the more hydrophilic DEVP as second comonomer was feasible (Table S1). Analysis of the molecular weight of the obtained copolymers was complicated due to aggregation, even at the low applied concentration in the GPC-MALS setup (and was verified via analysis of samples with different concentration). A more detailed study on REM-GTP copolymerizations is currently underway.

Some of us have reported previously on the synthesis of molecular brushes with poly(2-oxazoline) side chains and a PIPOx backbone via a *grafting-from* method using LCROP.[25] Since the backbone was prepared by free radical and anionic polymerization, the resulting molecular brushes were of broad molecular mass distribution. Herein, we use REM-GTP-prepared PIPOx as the backbone polymer. After reaction with

dx.doi.org/10.1021/ja4036175 | *J. Am. Chem. Soc.* 2013, 135, 8810−8813

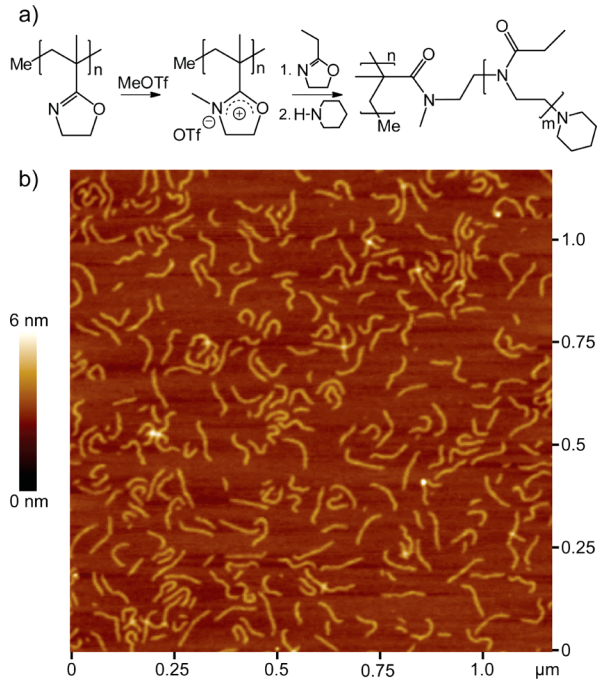

Figure 5. AFM scan of the molecular brush P(IPOx-*g*-EtOx). The polymer was deposited by dip-coating from a dilute chloroform solution onto freshly cleaved mica substrates.

methyl triflate, a polyoxazolinium salt is formed as a macroinitiator. Then, molecular brush side chains are formed by LCROP of 2-ethyl-2-oxazoline (EtOx) (Figure 5a). As verified by AFM measurements, all the molecular brushes adopt a stretched conformation due to the repulsion of poly(2-oxazoline) side chains (Figure 5b). Moreover, the contour length distribution is remarkably narrow, which corroborates the narrow molecular mass distribution of the PIPOx backbone. The combination of REM-GTP and LCROP is to our knowledge the first example for the synthesis of well-defined poly(2-oxazoline) molecular brushes with narrow side and backbone chain length distribution.

In conclusion, we have demonstrated an efficient method to prepare poly(2-isopropenyl-2-oxazoline) and poly(2-vinylpyridine) with high molecular weight and very narrow molecular-weight distribution via rare earth metal-mediated GTP. The present study is one of the first examples for REM-GTP to proceed via N−rare earth metal coordination. According to the highly living character of REM-GTP, the molecular weight of PIPOx and P2VP increased linearly with monomer conversion. We established a monomer reactivity order for REM-GTP as DEVP > MMA > IPOx > 2VP, which can be ascribed to the coordination strength of the respective monomers at the rare earth metal center. Consecutive polymerization of different monomers is hereby only possible in order of increasing coordination strength, and restricted to comonomers with similar polarity. Moreover, well-defined molecular brushes could be synthesized via the first combination of REM-GTP of IPOx and successive *grafting-from* LCROP of 2-oxazolines.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Detailed procedures and NMR spectra. 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.

■ ACKNOWLEDGMENTS

N.Z. acknowledges start-up funding from Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, and the National Natural Science Foundation of China. S.S. is grateful for a generous scholarship from the Fonds der Chemischen Industrie.

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