Terpyridines as Supramolecular Initiators for Living Polymerization Methods

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Summary: *Bis*(5,5"-*bis*(bromomethyl)-2,2':6',2"-terpyridine), *bis*-4'-(4-bromomethylphenyl)-2,2':6',2"-terpyridine and 4-hydroxymethyl-5',5"-dimethyl-2,2':6',2"-terpyridine metal complexes have been used as initiators for the living polymerization of 2-oxazolines and *L*-lactides. In both cases polymers with controlled molecular weights and narrow molecular weight distributions have been obtained. In-line diode array GPC measurements of iron(II) complexed poly(ethyloxazoline)s showed an unexpected absence of fragmentation. Viscosity experiments demonstrated the differences of the complexed and uncomplexed systems.

Introduction

Since bi- and terpyridines are very capable ligands to form stable transition metal complexes with interesting photochemical[1,2], electrochemical[3-5] or catalytic[4-8] properties, they have become a very active field of research. In order to combine these properties with tailor-made polymer materials, several paths have recently been described.[9-12] All these approaches result in more or less defined polymers with coordinative segments. One possible interesting application would be, e.g., the 'switching' of material properties (e.g. absorption/emission, viscosity, adhesion) due to the change of external conditions, such as, e.g., electrochemical, thermal or pH.

In order to obtain well-defined polymers with a determined number of chelating binding units, an effective concept is to use ligands or metal complexes as initiators for living polymerization procedures (e.g. polymerization of oxazolines, lactides or styrene). This concept has been well established for bipyridine systems by *Fraser* et al. as well as by our group.[13-20]

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In this context, terpyridines are only little investigated. Due to their higher complexation constants[21] and a large variety of possible functionalizations they are nevertheless very interesting. In this article we will present new aspects of the use of terpyridine based initiators for the living polymerization of oxazolines and a new approach to poly(lactide)s. In the end an entrance into multifunctional terpyridine initiators is discussed.

Experimental

For UV/VIS spectroscopy, a Varian Cary 3 UV/Vis Spectrophotometer was used. In-line diode array GPC measurements were carried out with a Waters 996 Photodiode Array Detector attached to a Waters 717plus Autosampler GPC. The viscosity measurements were carried out with an Ubbelohde viscosimeter, capillary I. The concentration of the decomplexed polymer was $7.52*10^{-5}$ mol/10 ml. After each measurement, a calculated amount of $FeSO_4 \times 7\ H_2O$ (~1 mg) was added to the solution (CH_3CN/CH_3OH; 1:1) until 100% of the polymer was fully complexed ($3.76*10^{-5}$ mol/10 ml) and no significant change in viscosity occurred.

Synthesis of terpyridine based supramolecular initiators for oxazoline polymerization: *Bis*(5,5"-*bis*(bromomethyl)-2,2':6',2"-terpyridine) iron(II) hexafluorophosphate (**3**) and *bis*-4'-(4-bromomethylphenyl)-2,2':6',2"-terpyridine iron(II) hexafluorphosphate (**1**) were synthesized according to published procedures (see ref[22]).

Poly(ethyloxazoline)s: Polymerizations were carried out in dry CH_3CN at 80 °C for 24 h according to ref[22,23]. After termination with piperidine and precipitation with diethyl ether, complexed poly(ethyloxazoline)s (**2**, **4**) were obtained.

Decomplexation of supramolecular poly(ethyloxazoline)s: The iron(II) and cobalt(II) complexes of the polymer were refluxed in a mixture of CH_3CN with aqueous K_2CO_3 (1 molar). After precipitation, colorless polymers were obtained (see ref[22]).

4-Hydroxymethyl-5',5"-dimethyl-2,2':6',2"-terpyridine (5): Synthesized according to ref.[24]. Selected analytical data: ^1H NMR ($CDCl_3$, 300 MHz): δ (ppm) 2.37 (s, 6H), 3.63 (s, 1H), 4.81 (s, 2H), 7.60 (m, 2H), 8.32 (s, 2H), 8.42 (d, 2H, J = 7.98 Hz), 8.46 (s, 2H); MS (EI): m/z 291 (M^+, 90%), 290 (M^+- 1, 100%).

*Poly(L-lactide)s (**6**):* The polymerizations were carried out in silanized schlenk tubes under nitrogen. 4-Hydroxymethyl-5',5"-dimethyl-2,2':6',2"-terpyridine (**5**) dissolved in dry toluene (10 mg/6 ml) and the aluminium triethyl in toluene (0.33 equivalents per OH unit) was added to the schlenk tube. The reaction mixture was stirred for 30 min at room temperature. Afterwards the monomer (3S)-cis-3,6-dimethyl-1,4-dioxane-2,5-dione was added (the amount was calculated with regard to the desired molecular weights) and the mixture was stirred at 80 °C for 2 days. The reaction was quenched with methanol. After removal of the solvent, the residue was dissolved in a small quantity of dichloromethane and afterwards poured into cold methanol. The precipitated polymer was filtrated and dried *in vacuo.*

Results and Discussion

Poly(oxazoline)s from terpyridine based supramolecular initiators: Poly(oxazoline)s are polymers whose solubility (polarity-) properties can be adjusted easily by changing the substituents in the 2-position of the monomers. Due to the living character of the cationic polymerization method, both chain-end functionalization and block copolymerization can be realized.[25]

Halomethyl functionalized bipyridine metal complexes have been used by *Fraser* et al. and *Schubert* et al. to initiate the polymerization 2-oxazolines. Molecular weight control, low polydispersities (PDI) and linear [monomer]/[initiator] versus molecular weight plots proved the living character of the polymerization.[15,26] By this method, block copolymers have been synthesized.[13,27] In addition, the termination of the polymer chains was carried out with different functional groups.[28]

We extended this concept to the use of supramolecular initiators with terpyridine ligands. Ligands with *bis*bromomethyl groups at the outer pyridine rings (5,5"-positions)[23,29] (**1**) and with one benzylbromide group attached to the central pyridine ring (4'-position)[22,30] (**3**) were synthesized (Figure 1). Stille-type cross-coupling is a suitable method to prepare terpyridines with substituents at well-defined positions, starting from simple pyridine building blocks. After further functionalization reactions, supramolecular initiators, in particular with Fe^{II}, Co^{II} , Zn^{II} and Ni^{II} as the central metal ions were prepared. Oxazoline polymerization was carried out mainly with the Fe^{II}

complexes; however, single poly(oxazolines) were also prepared with Co^{II}, Zn^{II} and Ni^{II} complexes (Figure 1). Polymerizations with both types of ligands were shown to be living.

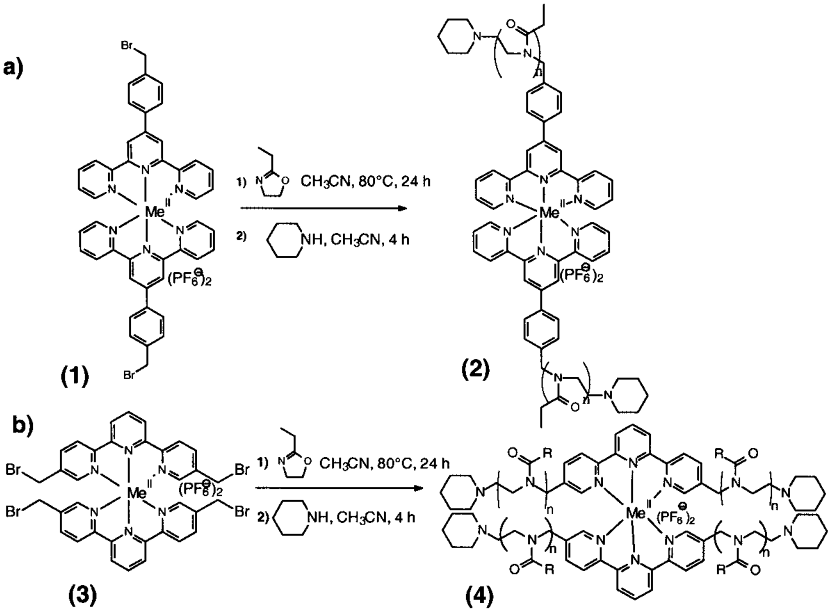

Figure. 1: Polymerization of 2-oxazolines utilizing supramolecular terpyridine based initiators.[22,23]

The polymer complexes can be cleaved by treatment with aqueous K_2CO_3. The incorporation of the metal ions in the polymers as well as the removal of the metal ion could be proven by UV/Vis spectroscopy. In order to examine the degree of reversibility of the complexation–decomplexation process, UV/Vis-titration experiments were carried out (Figure 2). It could be shown that recomplexation reaches up to 94%.[22] Titration of a decomplexed terpyridine terminated poly(ethyloxazoline) with $FeSO_4$ x 7 H_2O in CH_3CN/CH_3OH (1:1) was also performed in order to investigate the changes in viscosity behavior (Figure 3).

A typical 'ess' titration curve was obtained, showing a slight increase of viscosity at the point of equivalence. This could be expected in this case of a dimerization of the polymer. In contrast, the viscosity of star-like polymers – which can be obtained from (3) – should decrease compared to the open linear 'macroligands', caused by the smaller hydrodynamic radii of star-like polymers. Investigations concerning this subject are at present in progress.

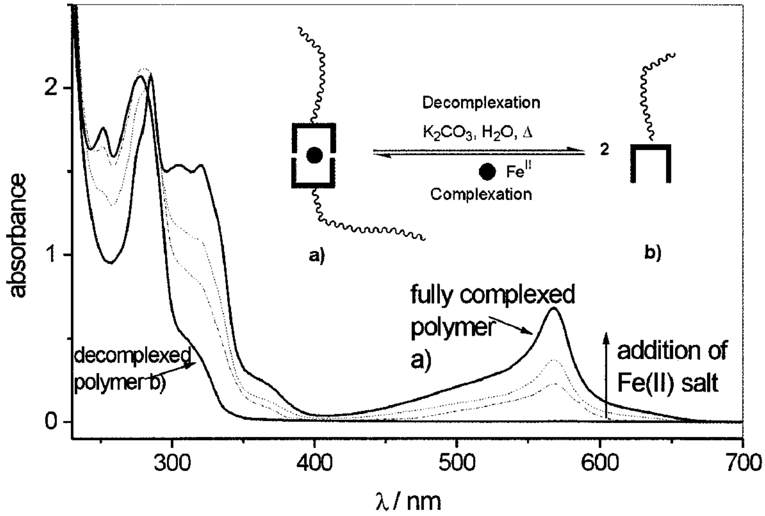

Figure 2: 'Supramolecular switching': UV/Vis-titration of a decomplexed poly(ethyloxazoline) solution with Fe^{II} salt.

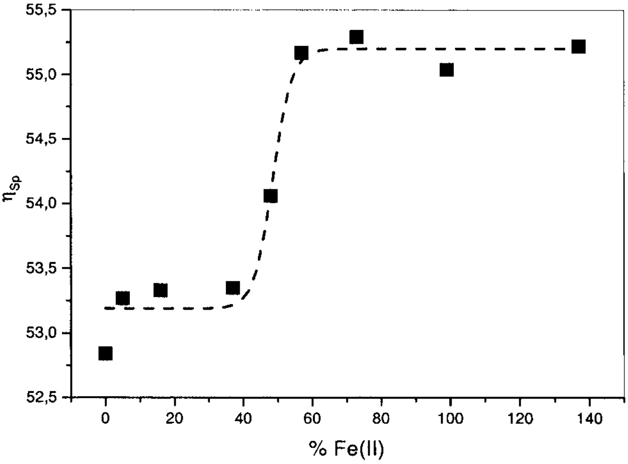

Figure 3: Changes of viscosity during titration of an uncomplexed poly(ethyloxazoline) ($7.52*10^{-3}$ mol/l, $M_n = 2660$) with $FeSO_4 \times 7\,H_2O$ in CH_3CN/CH_3OH (1:1).

It is noteworthy that the molecular weights of the Fe^{II}-centered terpyridine-poly(oxazoline)s measured by GPC were only about half the expected values of the monomer/initiator ratios. After decomplexation, no significant change of the molecular weight occurred. The same phenomenon was observed at bipyridine based supramolecular poly(oxazoline)s.[15,26] The comparatively labile Fe^{II}, Co^{II} or Cu^{II} containing polymer complexes were supposed to fragment on the GPC column due to shear forces. In-line multidiode array UV/VIS-spectroscopy is a suitable technique to study this phenomenon. *Fraser* et al. mentioned that the GPC fractions of the labile Fe^{II}-bipyridine based star-shaped polymer complexes contained little to no evidence of the red violet Fe^{II} *tris*(bipyridine) chromophores.[19,27] In contrast, the corresponding inert Ru^{II} compounds were completely eluted from the column without decomplexation.[18]

In the case of iron(II)-terpyridine based poly(ethyloxazoline)s (**2**), we could show that the complexes did not fragment on the GPC column. The whole UV/Vis-spectra of the $iron^{II}$ complexed polymer including the typical charge transfer band at 580 nm was detected by diode array UV/Vis detection (Figure 4). However, we cannot yet answer the question why the detected molecular weights are much lower than calculated.

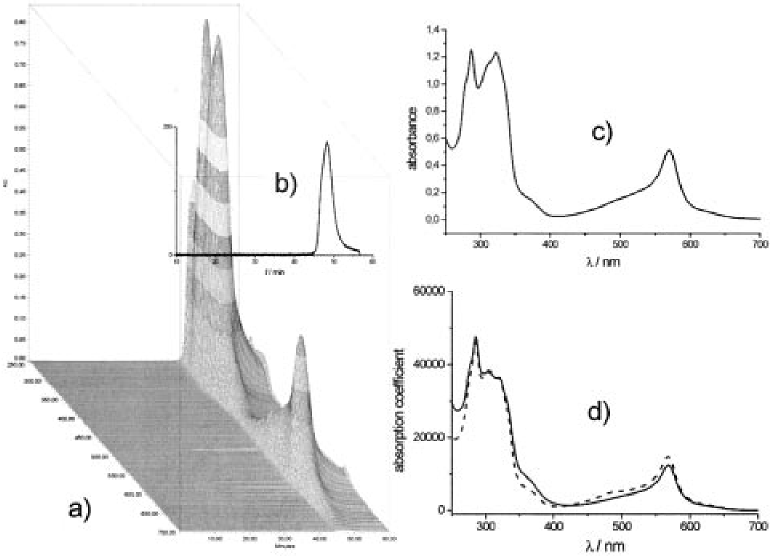

Figure 4: a) GPC-in-line diode array spectroscopy of a supramolecular Fe^{II}-poly(ethyloxazoline) (**2**) ($M_n = 3370$, $M_w = 5200$, PDI = 1.25). The x-axis represents the typical GPC curve, which is again shown in b) (RI detector). Along the y-axis the UV/Vis spectra is detected from 250-700 nm. c) shows a typical 2D-UV/Vis spectra which is the corresponding vertical section through the diode array curve. d) For comparison: UV/Vis spectra of the Fe^{II}-initiator complex (**1**) and a corresponding polymer (**2**).

Pol(lactides) from terpyridine based initiators: Poly(lactide)s are biodegradable polyesters which already found promising applications in medicine and tissue engineering.[31,32] Poly(lactide)s can be obtained via controlled coordinative ring-opening polymerization of lactides via aluminium alkoxides.[33,34] Hydroxymethyl substituted bipyridines were utilized recently as 'co-initiators' by *Schubert* et al.[35,36] and *Fraser* et al.[20,37] to yield bipyridine containing 'macroligands' or star-like polymer complexes. Meanwhile we extended this approach to terpyridine systems.

As co-initiator we utilized 4-hydroxymethyl-5',5"-dimethyl-2,2':6',2"-terpyridine (**5**) which can be prepared by reduction of 5',5"-dimethyl-2,2':6',2"-terpyridine-4-methylester (obtained using Stille-type cross-coupling reactions, see ref[24]). Polymerization of *L*-lactide yielded terpyridine end-capped poly(lactides) with controlled molar weight and very narrow polydispersities (Figure 5, Table 1). Further investigations are currently in progress.

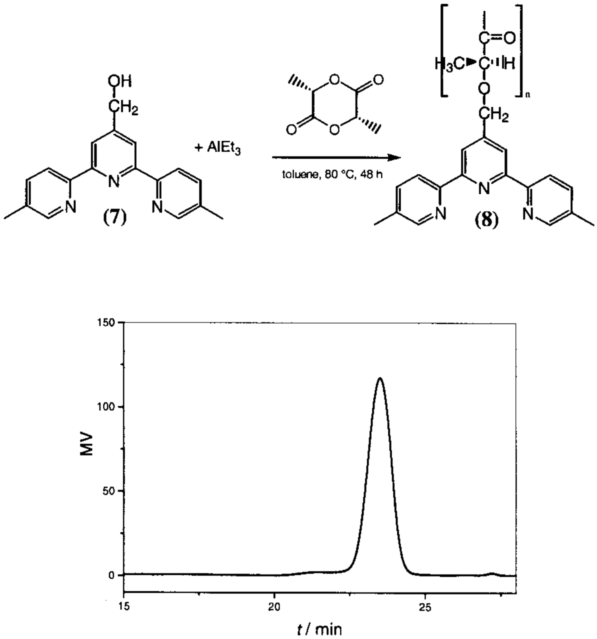

Figure 5: Polymerization of *L*-lactide with hydroxymethyl-functionalized terpyridine (**5**) as co-initiator.

Table 1: Various poly(*L*-lactide)s, polymerized utilizing co-initiator (**5**) (GPC data, polystyrene standards).

[M]/[I]	$\overline{M}_n$ (RI)	$\overline{M}_w$ (RI)	$\overline{M}_w/\overline{M}_n$	calculated masses [g/mol]
16	3020	3250	1.08	2600
30	5045	5450	1.08	4500
31	3840	6100	1.40	4660
32	7230	8100	1.12	4800
52	9240	9680	1.06	7700
147	17770	24690	1.39	21300
287	41790	45510	1.10	41500

Conclusions

We could demonstrate, that the concept of supramolecular initiators for living polymerization methods such as cationic polymerization of 2-oxazolines or coordinative polymerization of lactides can be easily transferred to terpyridine systems. Both of the obtained polymer types revealed narrow polydispersities and the molecular weight could be controlled. Central metal ions such as Fe^{II} (or Co^{II}) can be removed under basic conditions and can be introduced again almost quantitatively. Viscosity measurements on the titration of terpyridine end-capped poly(ethyloxazoline)s with Fe^{II} ions showed the increase of viscosity and the typical S-form-titration curve expected for the dimerization. Contrary to first assumptions, supramolecular Fe^{II}-terpyridine centered polymers do not fragment on GPC columns. There must be another reason for the finding of half the molecular weights of Fe^{II}-terpyridine-poly(ethyloxazoline)s compared to the molecular weight adjusted by [monomer]/[initiator] ratios. Further studies like light scattering experiments have to be carried out.

Outlook

The way to multifunctional supramolecular initiators: In this article we presented functionalized terpyridine initiators for the polymerization of oxazolines and lactides. The initiating groups and the resulting polymers were either at the outer pyridine rings

(1) or at the centered pyridine ring **(3)**. A promising extension of this concept would be the preparation of 'multifunctional' initiators – initiators with at least two different functional groups in one molecule (Figure 6). This would enable the grafting of two or more different polymers from one center or additional surface functionalization. Experiments in this direction are performed at present.

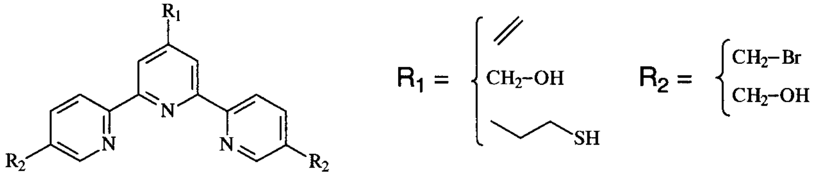

Figure 6: Schematically representation of a multifunctional supramolecular initiator.

Acknowledgements

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