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Communications to the Editor

Synthesis of Optically Active Helical Poly(3-methyl-4-vinylpyridine)

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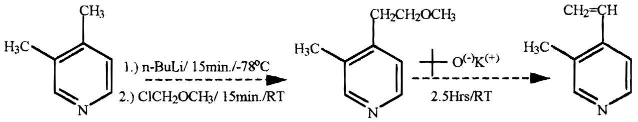
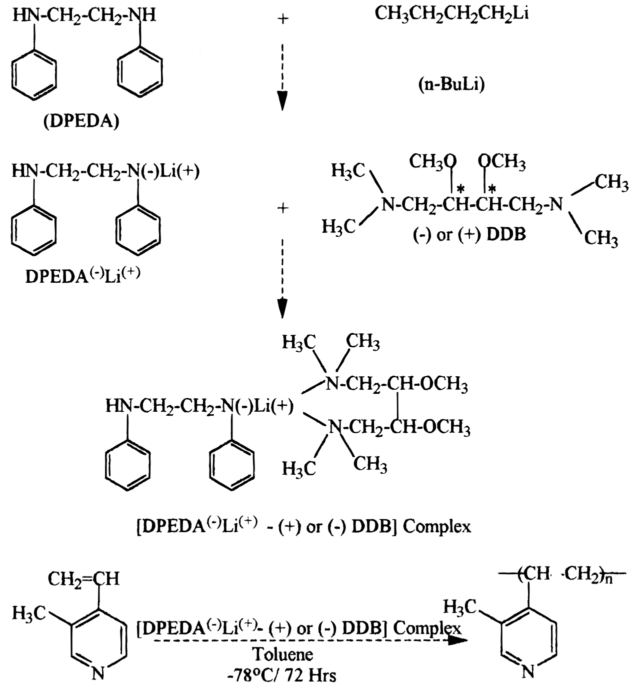
Introduction. There are many examples of synthetic macromolecules that have been demonstrated to have well-defined helical or secondary structures. Among the most comprehensively studied are the bulky methacrylates, which may be polymerized by chiral anionic initiators to obtain predominantly one-handed helical optically active polymers, e.g., poly(triphenylmethyl methacrylate) and poly(diphenyl-2-pyridylmethyl methacrylate).[1] These helical polymers are predominantly isotactic, and the stable helical conformation is maintained because the bulky side groups do not readily permit helix-to-helix interconversion. However, stereomutation has been observed for poly(diphenyl-2-pyridylmethyl methacrylate) at elevated temperatures.[2] Optically active helical polymers have been successfully utilized as chiral stationary phases with good optical resolving abilities in HPLC.[3] Other examples of optically active helical polymers include poly(isocyanates), poly(isocyanides), poly(N,N′-disubstituted acrylamide) and poly(chloral).[4−6] A number of interesting papers have recently reported on synthetic β-peptides with stable secondary structures or helical conformations.[7] The secondary helical structure of these β-peptides is possible because of intramolecular hydrogen bonding, whereas the optically active helical isotactic poly(bulky methacrylates) adopt the helical conformation because of steric reasons; i.e., the lowest energy conformation is the helix.

In this communication we report on the successful preparation of optically active helical poly(3-methyl-4-vinylpyridine) and demonstrate that bulky groups, e.g., triphenylmethyl, may not be necessary to carry out helix sense selective polymerization of vinyl monomers. Our motivation for this work results from a number of observations including the fact that in the solid-state isotactic α-olefins and certain substituted styrenes are known to be in a low energy helical conformation with a trans−gauche (...TGTG...) type backbone conformation. [8,9] Additional, observations include the preparation of isotactic poly(3-methyl-2-vinylpyridine) by anionic polymerization.[10] The isotacticity of this polymer is probably a result of a favored helical conformation caused by the nonbonded interaction between the 3-methyl group and the penultimate pyridine group.[11] It is not known if the helical conformation of poly(3-methyl-2-vinylpyridine) is energetically stable enough for preparing conformationally stable optically active polymers. The monomer, 3-methyl-4-vinylpyridine, was selected over 3-methyl-2-vinylpyridine because it is possible to successfully polymerize this monomer with softer anions such as lithium amides,[12] and lithium amide based optically active initiators are normally used to carry out helix sense selective polymerization.[1]

Scheme 1



Scheme 2. Synthesis of Optically Active Helical Poly(3-methyl-4-vinylpyridine)



Experimental Section. Monomer Synthesis. The monomer was synthesized using the method developed by Wright and co-workers[13] and is shown in Scheme 1. The monomer 3-methyl-4-vinylpyridine is obtained in 44% yield from 4-(β-methoxyethyl)-3-methylpyridine. ^{1}H NMR ($CDCl_3$), δ: 8.30 (s), 8.28 (d), 7.20 (d), 6.8 (m), 5.75 (d), 5.4 (d), 2.2 (s). Anal. Calcd: C, 80.73, H, 7.56, N, 11.76. Found: C, 79.37; H, 7.88; N, 11.42.

Polymerization. The polymerization was similar to the method reported by Okamoto (Scheme 2).[2] All anionic polymerizations were carried out using high vacuum breakseal techniques. The purity of the monomer was checked by GC-MS before preparing the breakseals containing the monomer, 3-methyl-4-vinylpyridine. The chiral anionic initiator DPEDA$^{(-)}$-Li$^{(+)}$−(+)- or (−)-DDB complex was prepared by first reacting diphenylethylenediamine (DPEDA) with *n*-

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Table 1. Polymerizations of 3-Methyl-4-vinylpyridine[a]

initiator	solvent	temp (°C)	time (h)	yield (%)	M_w	M_n
AIBN	benzene	60	72	3.2	17 700	17 000
n-BuLi	THF(10)/toluene (90)	−78	2	72		
LDA	THF(10)/toluene (90)	−78	16	66	36 800	36 000
DPEDA$^{(-)}$Li$^{(+)}$	toluene	−78	48	71	31 300	29 400

[a] GPC in toluene using Waters Styragel columns HR1, HR3, and HR4 at a flow rate of 1.5 mL/ min. Molecular weights are relative to polystyrene standards.

Table 2. Anionic Polymerization of 3-Methyl-4-vinylpyridine with the Complexes of DPEDA$^{(-)}$Li$^{(+)}$ with Optically Active Ligands[a−c]

run	chiral ligand	time (h)	$[\alpha]^{-4}_{589}$	M_w	M_n	concn (g/mL)[d]
1	(+)-DDB	72	(−)4.0			0.02
2	(−)-DDB	72	(+) 14.2			0.014
3	(+)-DDB	72	(−) 4.0	28 700	27 000	0.014
4	(−)-DDB	72	(+)14.7	14 000	13 000	0.014

[a] [monomer]/[initiator] = 70 in toluene. [b] GPC in toluene using Waters Styragel HR1, HR3, and HR4 at flow rate of 1.5 mL/min. Molecular weights are relative to polystyrene standards. [c] Indetermination value for [α] is ±0.1. [d] Concentration used in the determination of optical rotation.

BuLi at room temperature in toluene; this was followed by the addition of the chiral ligand (+)- or (−)-2,3-dimethoxy-1,4-bis(dimethylamino)butane [(+)-DDB or (−)-DDB] at room temperature and the complexation was allowed to proceed for 30 min at room temperature. The optical purities of the (−)-DDB and (+)-DDB were about the same with observed $[\alpha]_D^{20}$ values of −14.4 and +14.5, respectively. The molar ratio of the chiral ligand to the lithio anion was 1.2:1. After preparation of the chiral initiator, the breakseal containing 3-methyl-4-vinylpyridine was broken, and the monomer was added to the initiator solution maintained at −78 °C. The reactor was sealed and the polymerization was allowed to take place for 72 h at −78 °C. The yellow-orange solution of the living polymer was terminated by CH_3OH. Poly(3-methyl-4-vinylpyridine) was quickly precipitated into hexanes chilled with ice, most of the precipitating solvent was poured off, and the remaining hexanes/solid polymer mixture was filtered. The solid polymer was dried in a vacuum oven at room temperature for 12 h.

Characterization. ^{1}H and ^{13}C NMR spectra were obtained in a Bruker ARX 400 spectrometer, and ^{13}CP-MAS was obtained using Bruker MSL-200 spectrometer. Optical rotation was measured at −4 °C by a Rudolph Autopol III polarimeter in a cell with a path length of 1.0 dm. DSC thermograms were obtained using a Perkin-Elmer DSC-4 equipped with a thermal data station.

Results and Discussion. In Table 1, the polymerization conditions for 3-methyl-4-vinylpyridine using radical and different anionic initiators are listed. The low yield for the radically prepared polymer may be most likely because of a lower ceiling temperature (T_c) of the system. Because of steric reasons, the ceiling temperatures of α-methylstyrene and α-methyl-*o*-methoxystyrene are 0 and −25 °C, respectively.[14] Poly(3-methyl-4-vinylpyridine) is a white powder with an observed T_g of ~120 °C. Asymmetric anionic polymerization of 3-methyl-4-vinylpyridine with DPEDA$^{(-)}$Li$^{(+)}$/optically active ligand complexes was carried out at −78 °C in toluene, and the results are tabulated in Table 2. The polymers were precipitated into cold hexanes, and yields of the purified polymer were approximately 50%. Direct analysis by ^{1}H NMR of the polymeric reaction mixture upon termination by methanol indicated the absence of any residual monomer; i.e., most of the monomer under these conditions is converted to polymer. The 50% yield for the purified polymer is a result of the precipitation process used, where the hexanes is quickly poured out before all the polymer particles have had chance to settle to the bottom of the beaker. This strategy is applied so that helices do not undergo helix-to-helix interconversion during the purification process. The theoritical molecular weight of the optically active polymers, based on the monomer-to-initiator ratio, is around 8000, and the M_w and M_n, relative to polystyrene standards, determined by GPC results in an overestimation of the molecular weights. The GPC data also indicate that the molecular weight distributions of the optically active polymers are fairly narrow. The optical rotations of the polymers were measured in two ways: (a) as soon as the polymer was terminated at −78 °C by CH_3OH, a sample was taken out of the reaction flask and the rotation measured, and (b) the rotation was measured again after precipitation into cold hexanes. The $[\alpha]^{-4}_{589}$ values determined by both methods were consistent; a correction was applied to take into account the rotation due to the optically active ligand when method "a" was used. With the (+) DDB/DPEDA$^{(-)}$Li$^{(+)}$ initiating complex, polymers with $\sim[\alpha]^{-4}_{589}$ of −4.00 are obtained; while the (−) DDB/DPEDA$^{(-)}$Li$^{(+)}$ initiating complex produces polymers with $[\alpha]^{-4}_{589} \sim$ (+) 14.00. The difference in the observed optical rotations may have to do with a number of reasons including the diastereomeric transition states involved in the helix sense (left or right) selective polymerization and/or with the nature of the formation of the chiral initiating complexes and the energetics of the complexation.[15] The (2*S*,4*S*)-DDB and its enantiomer the (2*R*,4*R*)-DDB are used as chiral ligands. When the (2*S*,4*S*)-DDB chiral ligand is used, the diastereomeric transition states involved in the stereodifferentiation step would have the stereochemistry of either $[S,S,S^{\ddagger}]$ or $[S,S,R^{\ddagger}]$, where $S^{\ddagger}$ and $R^{\ddagger}$ denotes the stereocenters generated during the transition state. The difference in the energies of these two diasteromeric transition states determines the degree of stereoselection. However, when the (2*R*,4*R*)-DDB chiral ligand is used, the stereochemistry of the diastereomeric transition states would be either $[\mathrm{R,R,S}^{\ddagger}]$ or $[\mathrm{R,R,R}^{\ddagger}]$. The energy difference between the two sets of diastereomeric transition states do not have to be equal and, therefore, may be one plausible explanation for the difference in the observed optical activities, i.e., stereoselection. Additionally, a dependence on the molecular weight and molecular weight distribution on optical rotation is possible.[1] At −4 °C, the optical activity of homogeneous solutions of both the (−) and the (+) poly(3-methyl-4-vinylpyridine) decreased with time to zero rotation (see Figure 1). The loss of optical activity is most likely because of helix-to-helix interconversion resulting in racemization. Because helix-

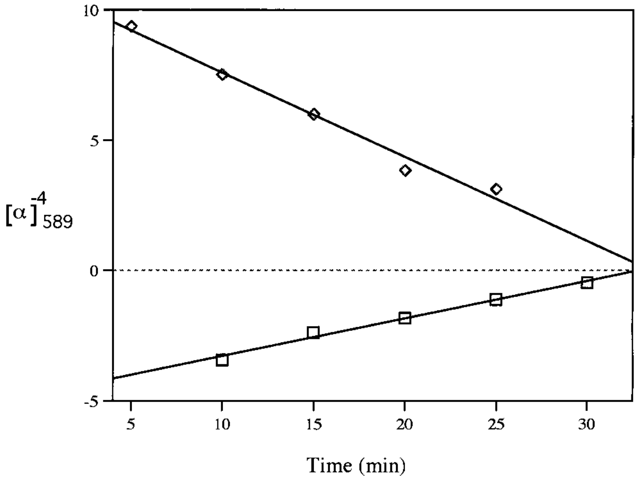

Figure 1. Loss of optical activity of (+)-, ◇, and (−)-poly(3-methyl-4-vinylpyridine), □.

to-helix interconversion is an intramolecular process and, hence, a zero-order kinetic process, one would expect a linear dependence of the loss of optical activity with time and this is observed in Figure 1. While in the solution at -4 °C, mutarotation is observed; the polymers are stable (i.e. no change in optical activity) in the solid state at room temperature or lower. The polymers may be stored in a refrigerator for several months without any loss of optical activity. Helix-to-helix interconversion is not observed in solution at -78 °C. These observations favor that some sort of higher structure, most likely secondary helical structure, is giving rise to the optical activity. The configuration of poly(3-methyl-4-vinylpyridine) has not been assigned, but comparison to poly(3-methyl-2-vinylpyridine) would seem to indicate that anionic polymerization should favor the formation of isotactic polymers.[10,11] The stereochemical characterization of poly(3-methyl-4-vinylpyridine) is currently underway using model oligomers.

Conclusion. Preliminary studies indicate that helix sense selective polymerization of 3-methyl-4-vinylpyridine is possible. The resulting secondary helical conformation is stable in the solid state and in the solution at -78 °C. This study raises the possibility of carrying out helix sense selective polymerization of monomers with fairly simple structures.

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(11) Intramolecular coordination of the metal ion by the penultimate pyridine nitrogen is highly unlikely in the poly(3-methyl-2-vinylpyridine) system as a result of the steric hindrance due the penultimate 3′-methyl group and has been demonstrated by studying the stereochemistry of methylation of 1-lithio-1-(2-pyridyl)-3-(3′-methylpyridyl)-butane. See: Mathis, C.; Hogen-Esch, T. E., *J. Am Chem. Soc.*, **1982**, 104, 634.

(12) With regards to a question raised by a reviewer, 3-methyl-4-vinylpyridine was selected over 3-methyl-2-vinylpyridine because this monomer may be polymerized with lithium amides in toluene. This has to do with the increased stability of the anion generated from the 3-methyl-4-vinylpyridine. Both monomers are polymerizable by *n*-BuLi in THF. Additionally, studies are available which report the initiation of 4-vinylpyridine by soft enolate anions, successful initiation of 2-vinylpyridine by such soft anions is not known. See: (a) Schulz, R. C. *Makromol. Chem., Macromol. Symp.* **1990**, 33, 1. (b) Li, J.; Khan, I. M. *Makromol. Chem.* **1991**, 192, 3043.

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