Notes

An Unequivocal Approach to Ascertain Asymmetric Induction in the Polymer Main Chain during Enantioselective Copolymerization of 1,2-Disubstituted Olefins†

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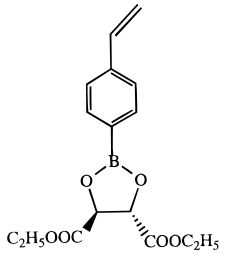
In general, polymerization of prochiral vinyl monomers using chiral auxiliaries and catalysts leads to formation of highly stereoregular (e.g., isotactic) polymers instead of optically active polymers.[1] This has been ascribed to the intriguing symmetry properties of macromolecular chains.[2] Thus, in order to realize optical activities in such polymers due to main chain chiral configuration, design of complex chain architecture is required that overcomes the symmetry properties of typical vinyl polymer chains arising from the repetitive insertion of monomer units which leads to mirror symmetry at a macromolecular level.[3] The primary paradigm for such structure is the introduction of local asymmetric configuration in a polymer chain in a regular manner. There exist two general schemes to achieve such structures: (i) copolymers based on 1,2-disubstituted olefins and (ii) 1-substituted olefin polymers consisting of a defined *n*-ad (*viz*. triad, tetrad, etc.) arrangement of monomer units. While the latter type of polymers have been reported recently,[4] the synthesis of the former type of polymer structures dates back to the work of Beredjick and Schuerch.[5] Unlike the polymers based on 1-substituted olefins alone which require sophisticated chain architecture to realize chiral structure, chiral chain structures in the case of copolymers of 1,2-disubstituted olefins with 1-substituted olefins are encountered more often.[2b] It is well-known that maleic acid derivatives (1,2-disubstituted olefin) typically undergo alternating copolymerization with styrenic and other electron rich 1-substituted olefins generating the desired chiral structures.[6] Thus, in the presence of a chiral auxiliary, chain propagation of such a copolymer system would occur in an enantioselective manner with predominant formation of one of the antipodes. In recent years different groups have pursued their studies pertaining to this class of 1,2-disubstituted olefin-based copolymers, with the objective of elucidating the influence of the type of chiral substituents, the nature of comonomers, and the polymerization conditions on the asymmetric induction in the polymer chain.[7] In all these studies, the chiral auxiliaries have been linked to the polymerizable moieties, through ester, amide, or ether linkages, whose quantitative removal becomes difficult even under harsh conditions.[8] The presence of residual pendant chiral units in the polymer chain renders difficulty in unambiguous assignment of the optical activity arising from chain configuration alone. In recent investigations of optically active vinyl and related polymers whose optical activity arises from main chiral configuration or conformation, it was observed that side chain chiral and achiral substituents significantly influence the observed optical activity of these polymers showing unusual chiroptical behavior.[9]

In order to ascertain asymmetric induction in this class of polymers unequivocally, we set out to utilize the principle of *protective group chemistry*[10] for linking the chiral auxiliaries to vinyl monomers. The protective group approach has enabled synthesis of a variety of soluble and cross-linked functional vinyl polymers possessing well-defined structures.[11] Futhermore, in chiral auxiliary-mediated asymmetric organic synthesis, it is documented that stereoelectronic structures of these auxiliaries as well as their location with respect to the prochiral center significantly influence the degree of asymmetric induction.[12] This implies that in the case of asymmetric polymerization the type of chiral auxiliaries and their location with respect to the double bond could influence the extent of asymmetric induction. We, therefore, set out to investigate the asymmetric copolymerization of maleimide derivatives (1,2-disubstituted olefin) with functional styrene monomers bearing chiral auxiliaries linked through easily removable protective groups, located at *para* and *ortho* positions with respect to the vinyl groups.

We selected the boronate ester of chiral diols as the protected functional group carrying a chiral auxiliary. Such linkages are known to be stable during free radical polymerization and yet can be cleaved quantitatively under mild condition (when desired) after polymerization.[13] The two monomers synthesized for this purpose were diethyl *O*,*O*-[(4-vinylphenyl)borylene]-L-tartarate (**1**) and diethyl *O*,*O*-[(2-vinylphenyl)borylene]-L-tartarate (**2**), which were obtained by reacting diethyl L-tartarate with (4-vinylphenyl)boronic acid and (2-vinylphenyl)boronic acid, respectively.[14] The chiral



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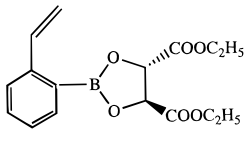

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monomers were copolymerized with *N*-phenylmaleimide in toluene under an inert atmosphere using AIBN as the free radical initiator. After achieving the desired conversion (<15%), the polymers were isolated and purified by repeated dissolution and precipitation from THF and petroleum ether, respectively. Infrared spec-

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Table 1. Chemical Composition and Specific Optical Rotation Values of the Copolymers of 1 and 2 with *N*-Phenylmaleimide

entry	mol fraction of chiral monomer in the copolymer[a]	$[\alpha]^{25}_{435}$[b] (deg) before removal of chiral auxiliary	$[\alpha]^{25}_{435}$[b] (deg) after removal of chiral auxiliary
		1	
1	0.36	−17.2	0.00
2	0.47	−21.0	−0.50
3	0.52	−22.0	−0.80
4	0.54	−21.5	−0.60
		2	
5	0.38	nd	−4.00
6	0.49	−5.00	−24.00
7	0.56	+3.00	−40.00
8	0.64	+12.00	−26.00

[a] Composition of the copolymers was estimated from the nitrogen content of the copolymers obtained from elemental analysis data. [b] Measurements were done with a filtered polymer solution at a concentration of 1 mg/mL in THF:water (90:10, v/v).

tra of the copolymers showed the presence of a 1728 cm^{-1} band due to the ester carbonyl stretching and absence of any hydroxyl stretching in the 3300−3500 cm^{-1} region. This suggests that the boronate ester groups were intact during polymerization and subsequent workup. The number-average molecular weights of these copolymers, as determined by GPC, were found to be in the range of 18 000−20 000. In order to elucidate enantioselective formation of optically active polymers possessing chiral configuration, quantitative removal of the chiral auxiliary is necessary. Following the reported literature procedure,[9b] we were able to remove the tartarate ester groups quantitatively from the polymer chain. This was verified from the infrared spectra of the hydrolyzed polymers (absence of 1728 cm^{-1} band) as well from the ^1H NMR spectra that showed the absence of the 3.9−4.2 ppm resonance due to the tartarate ester units.

Occurrence of asymmetric induction (if any) in these polymers was elucidated by investigating the chiroptical behavior of the pre- and posthydrolyzed copolymers based on the chiral monomers **1** and **2**. The specific optical rotation values of these copolymers along with their compositions are summarized in Table 1. In the case of copolymers based on **1**, all the samples showed negative optical rotations (see Table 1, entries 1−4). On the contrary, the copolymers based on **2** exhibited an interesting behavior. Copolymer with lower fraction of **2** in the chain was negatively rotating (Table 1, entry 6), while those with higher fraction of **2** showed positive optical rotations (Table 1, entries 7 and 8). The monomers **1** ($[\alpha]^{25}_D = -32°$) and **2** ($[\alpha]^{25}_D = +28°$) showed negative and positive rotations, respectively. Although, there is a nonlinear dependence of the specific rotation values on the copolymer composition (in comparison with calculated values), the effect is more significant in the case of **2**-based copolymers, where the chiral auxiliary is located closer to the double bond and hence polymer chain. The specific rotation values of chiral auxiliary free copolymers are quite interesting. While the hydrolyzed copolymers based on **1** virtually showed no optical activity, those based on **2** have appreciable optical rotations with a negative sign. The specific rotation values of these polymers also showed a composition dependency behavior. Thus, as can be seen from Table 1, the specific optical rotation reached a maximum with increasing concentration of **2** and then decreased. These observations clearly reveal the occurrence of asymmetric induction in the polymer backbone

Scheme 1

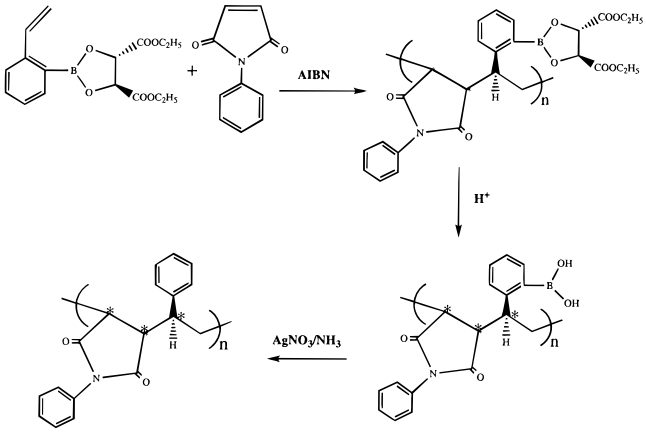

Table 2. Comparison of Specific Optical Rotation Values of the Chiral Auxiliary Free and Deboronated Copolymers of 2 with *N*-Phenylmaleimide

entry	mol fraction of **2** in the copolymer	$[\alpha]^{25}_{435}$ (deg) chiral auxiliary free copolymer[a]	$[\alpha]^{25}_{435}$ (deg) deboronated copolymer[b]
1	0.38	−4.00	−2.00
2	0.49	−24.00	−15.00
3	0.56	−40.00	−20.00
4	0.64	−26.00	−16.00

[a] Measurements were done with a filtered polymer solution at a concentration of 1 mg/mL in THF:water (90:10, v/v). [b] Measurements were done with a filtered polymer solution at a concentration of 1 mg/mL in THF.

that is critically dependent on the location of the chiral auxiliary with regard to the polymerizable double bond.[15]

In order to further confirm asymmetric induction in the polymer main chain with authenticity, the chiral auxiliary free copolymers based on **2** were subjected to chemical transformation to remove the boronic acid residues. Using $AgNO_3/NH_3$ reagent,[16] the boronic acid groups could be completely cleaved (as is evident from the complete disappearance of the 1305 cm^{-1} band in the IR spectra due to C−B−O stretching), thus offering styrene−*N*-phenylmaleimide copolymers. The above-mentioned sequence of reactions starting from polymerization to deboronation is illustrated in Scheme 1. Interestingly, these copolymers also exhibited negative optical rotations, similar to their precusor at all wavelengths (see Table 2). These findings clearly lend support to the fact that the optical activity of these copolymers is a consequence of enatioselective generation of chiral configuration of the polymer main chain. Although asymmetric induction in such type of polymers leading to optically active polymer has been clearly evident, the quantitative estimation of extent of asymmetric induction (% ee) is not known at the present time.

Although the term "main chain chirality" in the case of these types of copolymers based on 1,2-disubstituted olefins has been used in many contexts, we believe the present example is the real demonstration of the synthesis of such an optically active polymer chain. The rational design of monomer structure and subsequent chemistry thus enables the delineation of the role of the specific location of the chiral auxiliary with respect to the prochiral polymerizable double bond in asymmetric induction. While this parallels the observation made in the case of asymmetric organic synthesis, this is the first such example in polymer systems. The strategies

outlined here are general, and we hope that they can be applied to development of a vast array of functional chiral polymeric materials.

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(14) All new compounds reported in this communication gave satisfactory spectral and elemental analysis data as well as exact mass.

(15) During chain propagation, the maleimide double bond would open in both cis and trans fashion leading to *m* and *r* dyad, of which *r* has a C_2 symmetry axis (chiral). But, the presence of the adjacent styrene unit makes both possible triads chiral. (For details dealing with the stereochemical microstructures of such chiral polymer chains; see: ref 2b and Farina, M. *Top. Stereochem.* **1987**, *17*, 1.) While in an achiral environment, both the antipodes of the triads can be formed in equal probability; the presence of a chiral auxiliary would lead to predominant formation of one of the antipodes. The extent of asymmetric induction would depend on the stereoelectronic characteristics of the chiral auxiliary.

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