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Poly(quinoxaline-2,3-diyl)s Bearing (*S*)-3-Octyloxymethyl Side Chains as an Efficient Amplifier of Alkane Solvent Effect Leading to Switch of Main-Chain Helical Chirality

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Supporting Information

ABSTRACT: Poly(quinoxaline-2,3-diyl) containing (*S*)-3-octyloxymethyl side chains was synthesized to investigate the induction of a single-handed helical sense to the main chain in various alkane solvents. The polymer showed an efficient solvent dependent helix inversion between *n*-octane (*M*-helix) and cyclooctane (*P*-helix). After a screening of alkane solvents, it was found that linear alkanes having large molecular aspect ratios induced *M*-helical structure, and branched or cyclic alkanes having small molecular aspect ratios induced *P*-helical structure. A polymer ligand containing (*S*)-3-octyloxymethyl side chains and diphenylphosphino pendants also exhibited solvent-dependent helical inversion between *n*-octane and cyclooctane, leading to the highly enantioselective production of the both enantiomeric product in a palladium-catalyzed asymmetric hydrosilylation reaction of styrene (*R*-product 94% ee in *n*-octane and *S*-product 90% ee in cyclooctane).

By stabilizing or destabilizing chemical species in the ground, transition, and/or exited state through solvation, solvent effects play an important role in a variety of thermodynamic and kinetic chemical events. The interactions between solvent and solute are governed by various solvent properties, e.g. polarity, acidity, basicity, and the ability to form hydrogen bonds. Alkanes are generally considered as highly hydrophobic solvents, allowing an exclusion of most of the possibly occurring major solvent−solute interactions. This is also reflected in the family name of alkanes, which are commonly referred to as "*paraffins*", originating from the Latin *parum affinis*, meaning "little affinity".[1] Due to the minimal solvent−solute interactions, a change between alkane solvents hardly results in appreciable differences regarding the outcome of chemical events. Although alkane solvent effects have been investigated in detail with respect to spectroscopic properties, reaction selectivity, and equilibrium constants, no dramatic alternation has been observed. As far as small solute molecules are concerned, it seems to be difficult to pinpoint chemical events that show sharp changes induced by solvent effects between two alkane solvents.

However, one possibility to render the solvent effect between alkanes appreciable exists. Helical macromolecular scaffolds have been recognized as effective amplifiers for small local energy differences.[2] Green and co-workers clearly demonstrated the induction of a single-handed screw-sense by the sergeants-and-soldiers effect[3] and the majority-rule effect.[4] This feature of helical polymer backbones can be extended to the invertible induction of polymer helicity by means of external stimuli such as solvent change.[5] Even though the degree of helical sense induction, i.e., the screw-sense excess (se), remained moderate at low temperature (−10 °C), the inversion of the helical sense of a polysilane containing chiral side chains by changing the alkane solvent from *n*-octane (*P*-helix, 50% se) to isooctane (*M*-helix, 40% se) was one of the first examples of the aforementioned amplification effect.[5e] More recent examples showed that the helical supramolecular assembly can also be influenced by a change from *n*-heptane to methylcyclohexane.[6] These macromolecular and supramolecular helical scaffolds allow a clear observation of the solvent effect of alkanes through an appreciable change of the helical sense, which is unequivocally quantifiable by measuring the resulting circular dichroism (CD). Accordingly, the establishment of more sensitive helical scaffolds, in order to detect the solvent effects between alkanes, and to effectively apply the obtained knowledge in chemical processes seems to be highly desirable.

We have recently reported that poly(quinoxaline-2,3-diyl)s can serve as a new macromolecular scaffold, which undergoes a solvent-induced switch of helical chirality.[7] In our original system with (*R*)-2-butoxymethyl side chains, common organic solvents such as chloroform induce a *P*-helical sense, whereas 1,1,2-trichloroethane induces an inversion of the helical sense (*M*-helix). We also established a chirality-switchable helical polymer system of which main-chain helical chirality is inverted in *tert*-butyl methyl ether in contrast to other ether solvents.[8] These helical macromolecular scaffolds were subsequently used as ligands in polymer-based chiral catalysts with switchable chirality. In a variety of catalytic asymmetric reactions, both enantiomeric products could be generated with high enantioselectivities.[9] These helical scaffolds were also used for the fabrication of solid polymer films exhibiting switchable handedness, and a selective reflection of circularly polarized light, which could be tuned across the entire visible spectrum.[10]

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We envisioned that, once the chiral side chains are appropriately optimized, the use of new helical macromolecular scaffolds may provide us with the chance to observe otherwise unappreciable alkane solvent effects. Such scaffolds may also allow us to acquire new insights into the origins of the induction and inversion mechanisms of the helical sense. Herein, we demonstrate the highly selective induction of *P*- and *M*-helical structures in poly(quinoxaline-2,3-diyl)s with chiral side chains purely through the choice of alkane solvents. We also report the successful application of these helical macromolecules as chiral ligands with switchable chirality (*P*-/*M*-helix) for the preparation of asymmetric transition metal catalysts.

First, we prepared different polymers **1(100)**−**4(100)** with a degree of polymerization (DP) of 100, containing various chiral side chains. We then measured the CD spectra of **1(100)** with (*S*)-2-butoxymethyl side chains in *n*-hexane and cyclohexane (Figure 1a). The rod-like macromolecular shape of **1(100)**, with protruding chiral side chains, resulted in a good solubility in a variety of alkane solvents. Although **1(100)** exhibited, as previously reported, solvent-dependent helix inversion behavior between chloroform (*M*-helix) and 1,1,2-trichloroethane (*P*-helix),[7] **1(100)** retained an *M*-helical structure when being dissolved in either *n*-hexane or cyclohexane. Polymer **2(100)** with (*S*)-2-methylbutoxy side chains adopted, on the other hand, a *P*-helical structure in both *n*-hexane and cyclohexane. Although the helix sense of **2(100)** was found to be diametrically opposed to that of **1(100)**, neither exhibited a helix inversion between *n*-hexane and cyclohexane (Figure 1b). Polymer **3(100)**, bearing chiral (*S*)-2-octyloxymethyl groups, did not show a helix inversion either (Figure 1c). However, polymer **4(100)** with (*S*)-3-octyloxymethyl side chains clearly exhibited a solvent-dependent helix inversion between *n*-hexane and cyclohexane, even though the CD intensity was found to be relatively weak in the latter (Figure 1d). On the basis of these results, we considered **4(100)** to be a promising polymeric scaffold, in order to demonstrate the effective helix inversion induced by a change of alkane solvents.

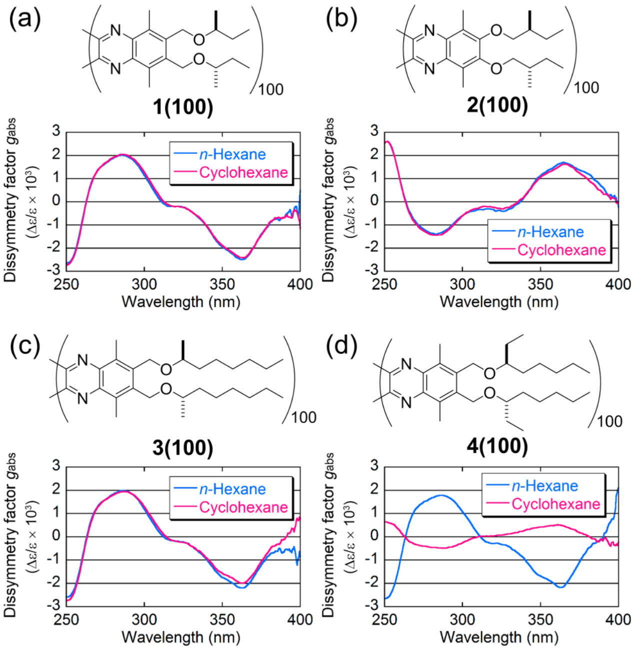


Figure 1. CD spectra of polymers **1(100)**−**4(100)** in *n*-hexane and cyclohexane. CD intensities are expressed as Kuhn's dissymmetry factor g_{abs} $(\Delta\varepsilon/\varepsilon)$.

Subsequently, we carried out an exhaustive screening of alkane solvents with respect to the solvent-dependent helix inversion of polymer **4(100)** (Figure 2a). For example, a series of linear *n*-alkanes (pentane to decane) induced exclusively an *M*-helical conformation. For branched or cyclic alkanes, trends with respect to the handedness of the helical chirality of **4(100)** were more complicated to be established. Whereas methyl-, ethyl-, propyl-, and butyl-substituted cyclohexanes induced an *M*-helix, unsubstituted cyclohexane, as well as isopropylcyclohexane induced a *P*-helix. On the basis of these results, it seems feasible to assume that the handedness of the induced screw-sense depends on the molecular shape of the alkane solvents.

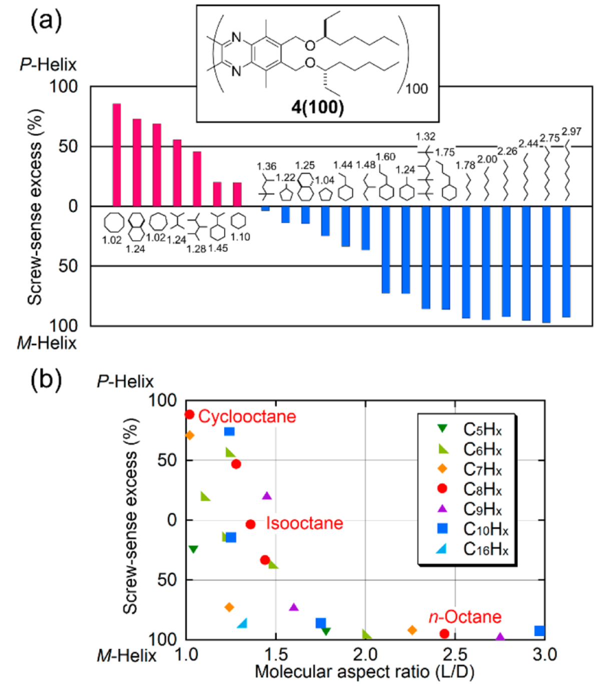


Figure 2. (a) Screw-sense excess (%) of polymer **4(100)** in various alkane solvents. Individual screw-sense excess values were determined on the basis of CD intensities. Values for the molecular aspect ratio (L/D) of the alkane solvents are also shown. (b) Relationship between the screw-sense excess of polymer **4(100)** and the molecular aspect ratios of various alkane solvents, which were classified according to the number of carbon atoms.

We focused our attention in the following on the relationship between the molecular shape of the alkane solvents and the resulting screw-sense excess of polymer **4(100)**. In order to evaluate the molecular shapes of various alkane solvents quantitatively, we adopted the molecular aspect ratio value,[6a,11] which is defined as the ratio between the length of the major axis (L) and the minor axis (D) of a given molecule after performing a geometry optimization by the CONFLEX program.[12] We found that the screw-sense excess of **4(100)** is clearly correlated with the molecular aspect ratios of the alkane solvent (Figure 2b). When examining saturated hydrocarbons with 8 carbon atoms for example, *n*-octane exhibited a relatively large molecular aspect ratio (L/D = 2.47), which selectively induced an *M*-helical structure (95% se). In contrast to that, isooctane showed only a moderate molecular aspect ratio (L/D = 1.35), which resulted in the formation of nearly racemic mixtures of *P*- and *M*-helices (*M*-helix, 4% se). Cyclooctane, on the other hand, with a relatively small molecular aspect ratio (L/D = 1.02), was able to efficiently induce a *P*-helical structure (86% se). It is important to mention here that no other correlation between the induction of screw sense and any other solvent properties of the alkanes such as polarity, permittivity, molecular volume, or topological indexes[5e] was observed (see SI).

We were then interested in achieving high screw-sense excess values in the pair of the alkane solvents, in which an efficient helix inversion could be ensured. Therefore, we prepared a series of polymers **4(DP)** with varying degrees of polymerization (DP = 30−300), containing (*S*)-3-octyloxymethyl side chains. These polymers should allow an exact determination of the energy difference gained per monomer unit (ΔG_h) in cyclooctane or *n*-octane, respectively. In accordance with Green's theory,[13] the observed screw-sense excess values increased nonlinearly with the increase in DP (Figure 3a). The ΔG_h values were found to be 0.06 and 0.10 kJ/mol in cyclooctane and *n*-octane, respectively, which is smaller compared to our previously reported polymer systems.[7] At 20 °C, a DP of 250 was found to be sufficient in order to induce absolute *P*- or *M*-helices (>99% se) in *n*-octane or cyclooctane. The CD spectra of polymer **2(250)** in *n*-octane and cyclooctane are almost perfect mirror images of each other, indicative of an almost perfect solvent-dependent helix inversion (Figure 3b).

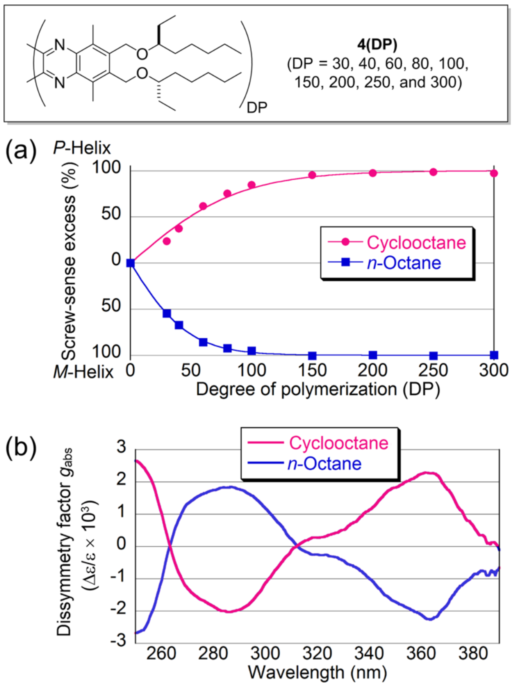
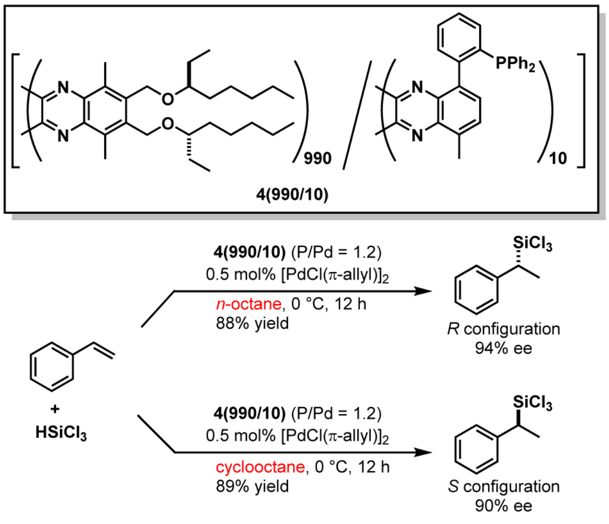


Figure 3. (a) Correlation between the degree of polymerization (DP) and the screw-sense excess (se) of polymers **4(DP)** (DP = 30−300). (b) CD spectra of polymer **4(250)** in cyclooctane and *n*-octane.

Finally, we demonstrate a conceivable catalytic applications of the obtained *P*- and *M*-helical structures of polymer **4** in cyclooctane or *n*-octane, e.g., in an asymmetric hydrosilylation reaction. In one of our previous papers,[9b] a polymer ligand containing (*R*)-2-butoxy side chains and 2-(diphenylphosphino)phenyl pendants was used in the asymmetric hydrosilylation of styrenes. Therefore, we prepared the random copolymer **4(990/10)** bearing (*S*)-3-octyloxymethyl side chains and 2-(diphenylphosphino)phenyl pendants as a chiral polymer ligand for the asymmetric hydrosilylation of styrene with trichlorosilane (Scheme 1). When the reaction was carried out in *n*-octane, which induced an *M*-helical polymer backbone, the major reaction product had (*R*)-configuration (94% ee), whereas when the same reaction was carried out in cyclooctane, the (*S*)-product was obtained in high enantioselectivity (90% ee). This result clearly demonstrates that highly enriched *P*- and *M*-helical structures of **4(990/10)** are induced in *n*-octane or cyclooctane, which is in good agreement with our estimations based on the CD measurements.

Scheme 1. Palladium-Catalyzed Asymmetric Hydrosilylation of Styrene in *n*-Octane or Cyclooctane Using Chiral Copolymer 4(990/10) as a Ligand



In summary, we have investigated the induction of a single-handed helical sense in the main chain of poly(quinoxaline-2,3-diyl)s containing chiral (*S*)-3-octyloxymethyl side chains in various alkane solvents. We observed a clear correlation between the handedness of the induced screw-sense and the molecular aspect ratio of the alkane solvents. Linear alkanes with larger molecular aspect ratios induced *M*-helical structures, whereas branched or cyclic alkanes with smaller molecular aspect ratios induced *P*-helical structures. Finally, we demonstrated that a random poly(quinoxaline-2,3-diyl) copolymer containing (*S*)-3-octyloxymethyl and 2-(diphenylphosphino)phenyl side chains can serve as a highly enantioselective chiral ligand in the palladium-catalyzed hydrosilylation of styrene in alkane solvents. The copolymer was observed to undergo a solvent-dependent helical inversion between *n*-octane and cyclooctane, leading to a highly enantioselective production of both enantiomeric products. Further studies exploring potential applications of helical poly(quinoxaline-2,3-diyl)s with switchable chirality as a new class of chiral supporting materials are currently undertaken in our laboratory, together with systematic investigations into the origin and mechanism of this solvent-dependent helix inversion.

ASSOCIATED CONTENT

Supporting Information

Experimental procedures and spectral data for the new compounds. 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.

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