Helical Structures

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Supramolecular Helical Structure of the Stereocomplex Composed of Complementary Isotactic and Syndiotactic Poly(methyl methacrylate)s as Revealed by Atomic Force Microscopy**

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The DNA double helix composed of complementary strands is of fundamental importance for the exquisite functions of DNA, such as the replication and storage of genetic information. Since the discovery of the DNA double helix,[1] the design and synthesis of artificial double helices have attracted significant attention but remain a great challenge in polymer and supramolecular chemistry.[2] In particular, double helices of complementary strands are quite rare.[3]

The complex formed from complementary strands of isotactic and syndiotactic poly(methyl methacrylate)s (*it*- and *st*-PMMAs) with an *it*/*st* stoichiometry of 1:2 is commonly described as a stereocomplex and represents a class of unique, polymer-based supramolecules with an apparent melting point in specific solvents.[4] Although the stereocomplex has been known for half a century, the molecular basis of the structure and the mechanism of complex formation are still under debate, in spite of its availability as advanced materials, such as ultrathin films,[5] thermoplastic elastomers,[6] and dialyzers.[7] It is also a versatile structural motif for stereospecific template polymerization[8] in connection with abiotic replication.

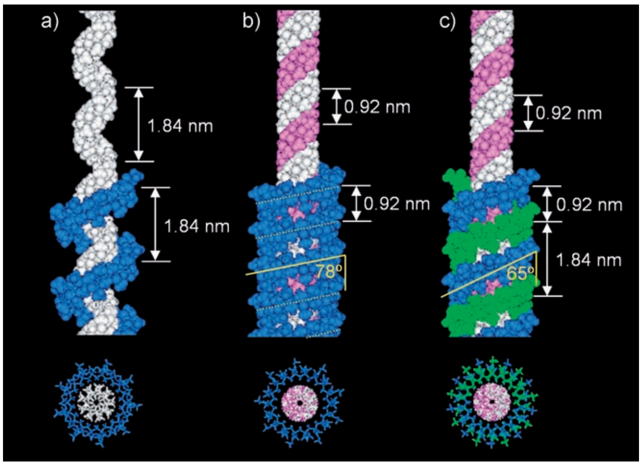

Figure 1. Space-filling models (top: side view) and stick models (bottom: cross-section) for an *it*- and *st*-PMMA stereocomplex (*it*/*st* = 1:2): a) double-stranded helix;[9] b) triple-stranded helix; c) quadruple-stranded helix (white and pink: *it*-PMMA helix; blue and green: *st*-PMMA helix). The upper part of the *st*-PMMA helix is omitted for clarity.

In 1989, Schomaker and Challa proposed a reliable model for the PMMA stereocomplex on the basis of X-ray analysis of the stretched fiber, that was the double-stranded helix composed of a 9_1 *it*-PMMA helix (nine repeating MMA units per turn) surrounded by a 18_1 *st*-PMMA helix with a helical pitch of 1.84 nm (Figure 1 a).[9] Since then, the double-stranded-helix model has been commonly accepted, because the model could explain rationally 1) the stoichiometry of an asymmetric unit (*it*/*st* = 1:2),[4] 2) the template-polymerization phenomena,[8] and 3) the fact that stereocomplexation also took place between *it*-PMMA and *st*-poly(methacrylic acid), and even when the methyl ester groups of *st*-PMMA were replaced by other alkyl groups, whereas the methyl esters of *it*-PMMA were essential for the stereocomplexation.[4,10] However, because of the limited number of diffuse X-ray diffractions, the complicated structure of the PMMA stereocomplex was difficult to determine by X-ray diffraction, and the proposed double-helix model may require further reconsideration.

Although the structural elucidation of helical polymers at a molecular level by X-ray diffraction is a laborious task even now, recent significant developments in microscopic instruments coupled with precise polymerization techniques have made it possible to observe directly the helical structures of certain helical polymers. In fact, we succeeded recently in observing the helical structures of helical poly(phenylacetylene)s and polyisocyanides by high-resolution atomic force microscopy (AFM).[11] These polymers self-assembled into two-dimensional (2D) helix bundles on substrates upon exposure to organic-solvent vapors. This 2D structure enabled the determination of the molecular packing, helical pitch, and handedness (right- or left-handed helix) by AFM. We also visualized successfully by AFM the molecular structure of the 2D crystals of *it*-PMMA in a Langmuir–Blodgett (LB) film

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deposited on mica; the 2D folded-chain crystals assembled from single chains together with tie chains were observed for the first time.[12] *it*-PMMA is believed to form a double-stranded helix in the crystals; however, the molecules were too thin and narrow for us to determine the helical structure. We anticipated that if the PMMA stereocomplex really was a large double helix as proposed (Figure 1a) and could be further assembled into 2D crystals on substrates, it might be possible to visualize the double-stranded helical structure by AFM.

A mixed monolayer of *it*- and *st*-PMMA chains spread on a water surface is known to form a stereocomplex upon compression on the basis of the surface pressure-area (π-A) isotherms and IR spectra of the resulting thin films.[13] Figure 2 shows the π-A isotherms of an *it*-PMMA (number-average molecular weight (M_n): 12000, polydispersity index (PI): 1.11, $[mm] = 97\,\%$), an *st*-PMMA (M_n: 13000, PI: 1.13, $[rr] = 96\,\%$), and a mixture of the two polymers (*it*/*st* = 1:2).[14] The *it*-PMMA exhibits a typical expanded π-A curve with a transition at around $10\ \mathrm{mN\,m^{-1}}$, which corresponds to its crystallization into lamellar crystals (thickness: ca. 0.5 nm; Figure 2a and Supporting Information), whereas the *st*-PMMA shows a compressed π-A curve without any apparent transition, and forms continuous films without any specific structures (Figure 2a and Supporting Information), as previously reported.[12,15]

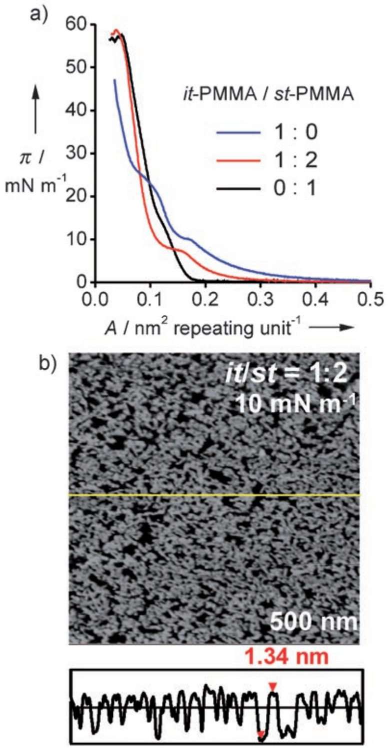

Figure 2. a) π-A isotherms of *it*-PMMA, *st*-PMMA, and an *it*- and *st*-PMMA mixture (*it*/*st* = 1:2) on water. b) AFM height image (500 nm × 500 nm) of a monolayer of the *it*- and *st*-PMMA mixture deposited on mica at $10\ \mathrm{mN\,m^{-1}}$, with the height profile along the yellow line.

The mixture with an *it*/*st* stoichiometry of 1:2 showed a completely different π-A curve with a transition at a lower π value of around $7\ \mathrm{mN\,m^{-1}}$, which corresponds to the stereocomplexation (Figure 2a).[13] The AFM images indicated that the *it*- and *st*-PMMA chains were phase separated at $1\ \mathrm{mN\,m^{-1}}$ (see Supporting Information), but formed a new crystalline phase with a thickness of approximately 1.3 nm at $10\ \mathrm{mN\,m^{-1}}$ (Figure 2b). This crystalline phase was completely different from the monolayers of each component, which suggests the quantitative formation of the crystalline stereocomplex.[16] The formation of a stereocomplex was also supported by IR measurements of the LB films (see Supporting Information).[13a]

We then obtained high-resolution AFM images of the stereocomplex deposited on mica at $10\ \mathrm{mN\,m^{-1}}$ to gain concrete evidence for the helical structure of the stereocomplex. Interestingly, the AFM images revealed well-defined helix-bundle-like structures with an average height of 1.4–1.6 nm, which were further resolved into individual stripe-patterned chains with a clear chain–chain lateral spacing of (2.4 ± 0.1) nm (Figure 3a and Supporting Information). The high-resolution AFM zoomed image (Figure 3b) provided more convincing evidence for the helical structure in the form of a number of periodic oblique stripes (yellow

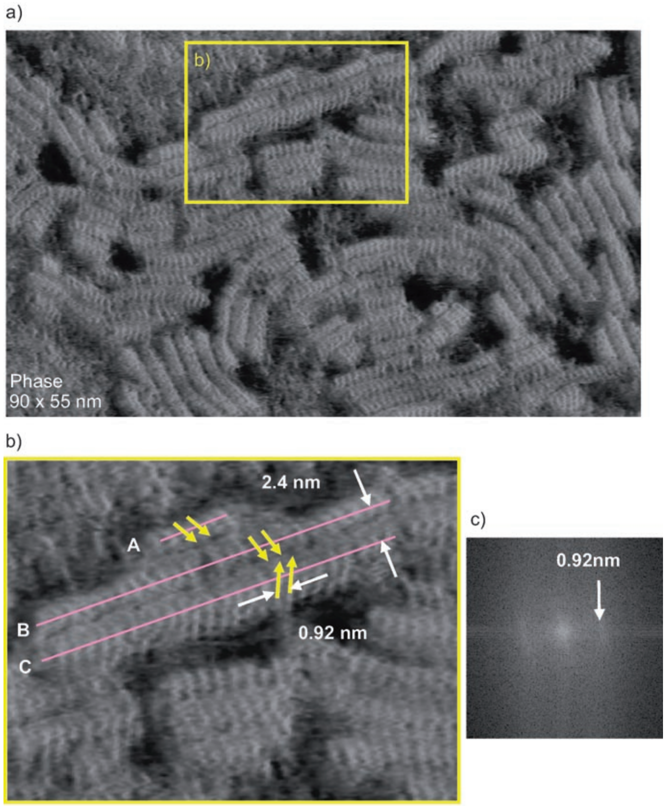

Figure 3. a) AFM phase image of a monolayer of an *it*- and *st*-PMMA mixture (*it*/*st* = 1:2) deposited on mica at $10\ \mathrm{mN\,m^{-1}}$. b) Magnified image of the area indicated by the yellow square in (a); the pink lines represent the main-chain axes of the stereocomplex; the yellow arrows indicate the antipodal oblique pendant helical arrangements with respect to the main-chain axes. c) Typical Fourier transform of a section of (a).

arrows in Figure 3 b) along the stereocomplex main chain (pink lines). These stripes probably originate from a one-handed helical array of the pendants, which are tilted either counterclockwise or clockwise with respect to the axis of the stereocomplex main chain. Figure 4 shows the distribution of the tilt angles of the periodic oblique stripes as determined for 42 stereocomplex chains with an apparent helical structure in a section of Figure 3 a. The number-averaged tilt angles for the left- and right-handed helices were found to be (−74.4 ± 7.3)° and (73.5 ± 4.6)°, respectively. These remarkable enantiomerically tilted, mirror-image stripes revealed a helical pitch of (0.92 ± 0.02) nm (see also Figure 3 c), which confirms that the PMMA stereocomplex is a helical polymer-based supramolecule.[17] Furthermore, each stereocomplex probably consists of a fully right- or left-handed helix; however, the overall structure is effectively racemic and composed of small domains made of right- or left-handed helices.

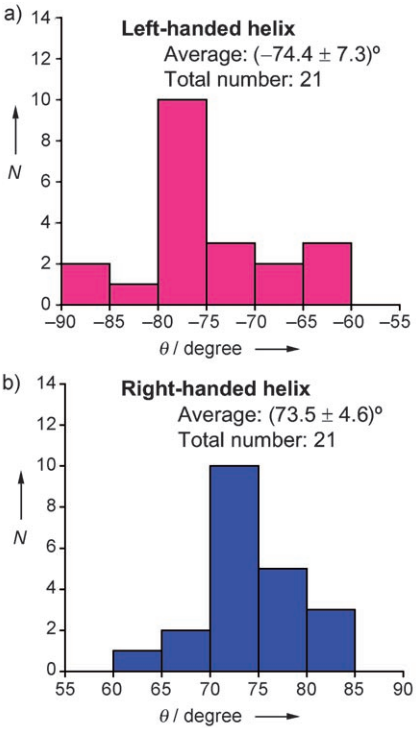

Figure 4. Distribution of the tilt angles of the periodic oblique stripes (yellow arrows in Figure 3 b) with respect to the axis of the stereocomplex main chain (pink lines) for 42 stereocomplex chains in a section of Figure 3 a. For the assignment and spatial distribution of the right- and left-handed helices in the image, see the Supporting Information.

The chain–chain distance estimated by AFM is in good agreement with the width of the double-stranded-helix model (ca. 2.4 nm; Figure 1 a). However, the observed helical pitch of 0.92 nm corresponds to only half of the proposed value (1.84 nm), which suggests that the double-helix model for the PMMA stereocomplex requires major revision.

It has been found experimentally that the stereocomplex forms quantitatively at a ratio of *it*- to *st*-PMMA of 1:2. Thus, we can deduce that the *st*-PMMA chain winds regularly around the *it*-PMMA chain at the unit molar ratio (*it*/*st* = 1:2). On the basis of this ratio and the AFM results (in particular, the helical pitch of the stereocomplex), we propose a triple-stranded helix as a more plausible model for the helical structure of the stereocomplex (Figure 1 b): A double-stranded helix composed of two 9_1 *it*-PMMA helices with a helical pitch of 1.84 nm is surrounded by a 18_1 *st*-PMMA helix with the observed helical pitch of 0.92 nm. This model satisfies both the experimental results and the stoichiometry of the stereocomplex.

The double-stranded helical structure of *it*-PMMA crystals was proposed by Kusanagi et al. on the basis of X-ray analysis.[18] In this model, two 10_1 helices of *it*-PMMA chains are intertwined to form a double helix in the crystals. We proved recently the validity of the model on the basis of high-resolution AFM observations of an *it*-PMMA LB film.[12] We modified the *it*-PMMA double helix from the 10_1 helix to a 9_1 helix to fit the X-ray results of the PMMA stereocomplex in our model (Figure 1 b).

On the other hand, it is known that *st*-PMMA does not crystallize, but cocrystallizes in specific organic solvents, such as cyclohexanone and benzene, as a result of inclusion complexation with the guest molecules in a cavity of the generated helical *st*-PMMA helices.[19] The helical structure was postulated to be a 74_4 helix with a helical pitch of 0.885 nm and an inner diameter of approximately 1.2 nm on the basis of X-ray analysis. The 74_4 (= 18.5_1) helix of *st*-PMMA is almost identical to the helical structures of the *st*-PMMA component of the stereocomplex (18_1 helix) that were proposed for the double-stranded-helix (Figure 1 a) and triple-stranded-helix (Figure 1 b) models, but the helical pitch (0.885 nm) is in close agreement only with that determined by AFM (0.92 nm) and therefore with the triple-stranded-helix model. These results support our proposed stereocomplex structure (Figure 1 b) and provide important information for understanding the principle that underlies the formation of the PMMA stereocomplex. Thus, the helical *st*-PMMA possesses a cavity for inclusion complexation with an *it*-PMMA double helix that fits the cavity size.[20]

Another model for the PMMA stereocomplex, a quadruple-stranded helix that also satisfies the AFM results and the stoichiometry *it*/*st* = 1:2, may be possible in principle (Figure 1 c). In this model the same double-stranded helix of *it*-PMMA is surrounded by a double-stranded helix composed of two intertwined 18_1 *st*-PMMA helices with the observed helical pitch of 0.92 nm.[21] A major difference between the two models (Figure 1 b,c) is the difference in the tilt angle of the outer *st*-PMMA helix with respect to the axis of the stereocomplex main chain: Tilt angles of 78 and 65° were found for the triple- and quadruple-stranded helices, respectively. The observed tilt angle of approximately 74° (Figure 4 and Supporting Information) as estimated by AFM is in fair agreement with the tilt angle of the triple-stranded-helix model.

In conclusion, we have provided direct evidence by AFM with molecular resolution for the helical structure of the PMMA stereocomplex, a long-standing question in polymer chemistry, and proposed a triple-stranded-helix model. The present results suggest that the PMMA stereocomplex may not be an intertwined double helix composed of complementary single *it*- and *st*-PMMA chains, but may be a supramolecularly assembled inclusion complex that consists of an outer *st*-PMMA helix and an inner *it*-PMMA double helix. We emphasize that AFM is a powerful alternative method for obtaining directly key structural information about complicated supramolecular structures. Such structures are difficult to determine by conventional X-ray diffraction measurements. Further studies, including optimization of the helix model by X-ray diffraction of highly oriented fibers and the helix-sense-selective synthesis of the PMMA stereocomplex, are in progress.

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[14] These highly stereoregular PMMAs with a narrow molecular-weight distribution were synthesized by stereospecific anionic living polymerization; see the Supporting Information for detailed procedures.

[15] For the changes in morphology upon compression of the *it*- and *st*-PMMAs and their mixtures with a different *it*/*st* mixing ratio, see the Supporting Information.

[16] When the mixture $it/st = 3{:}1$ was used, phase-separated crystalline domains composed of *it*-PMMA lamellae and the stereocomplex were observed (see Supporting Information).

[17] In addition to AFM, we measured grazing-incident X-ray diffraction (GIXD) of the stereocomplex LB films with synchrotron radiation as the X-ray source. The samples were composed of between one and fifteen layers of the stereocomplex LB films of the *it*- and *st*-PMMA monolayers ($it/st = 1{:}2$) deposited on silicone wafers at $10\ \mathrm{mN\,m^{-1}}$. Diffractions from the samples were detected in the in-plane direction by a scintillation counter. However, no apparent scattering peaks from the LB films were observed, probably because of extremely weak scattering as a result of the large crystalline unit size and the random orientation of the stereocomplexes on the substrates.

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[20] Molecular modeling and molecular-dynamics (MD) simulations indicate that the triple-stranded helix is stable and maintains its structure during the MD annealing process at 400 K for 200 ps.

[21] Schomaker and Challa also identified a similar four-stranded helical structure as a possible stereocomplex model, as the observed X-ray layer-line reflections, especially the weakness of the first layer line corresponding to a spacing of 1.84 nm, could not be explained clearly with respect to the proposed double-stranded-helix model.[9] Both our triple-stranded-helix model and our quadruple-stranded-helix model with a helical pitch of half that of the double-helix model offer a rational explanation for the weakness of the first-layer-line reflection.