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Construction of Double-Stranded Metallosupramolecular Polymers with a Controlled Helicity by Combination of Salt Bridges and Metal Coordination

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Multiple-stranded helical structures are ubiquitous in Nature, particularly in biomacromolecules, such as DNA and collagen.[1] They are constructed through the cooperative action of several noncovalent forces and are significantly linked to their elaborate biological functions. Inspired by the biopolymers with multiple-stranded helical structures, chemists have exerted much effort to intertwine artificially designed oligo- or macromolecular strands to form multiple-stranded helical structures by utilizing noncovalent interactions.[2] We have recently reported the rational design and synthesis of complementary double helices with optical activity, of which the strands consist of crescent-shaped *m*-terphenyl groups bearing chiral amidine and achiral carboxyl groups.[3] The double helix formation with a controlled helicity is driven by the chiral amidinium−carboxylate salt bridges, which are tolerant to other various functional groups, thereby making a wide range of designs possible.[4]

Supramolecular polymerization has recently emerged as a new protocol to synthesize macromolecules by holding together small molecules through noncovalent bonds, and a number of such supramolecular polymers have been reported to date.[5] However, to the best of our knowledge, double-stranded supramolecular helical polymers stable in solution are hitherto unknown.[6] With the aim of constructing double-stranded metallosupramolecular helical polymers with optical activity, we designed new amidinium−carboxylate duplexes bearing pyridine groups at the four ends, $\mathbf{1^{R}\cdot 2}$ and $\mathbf{1^{S}\cdot 2}$ (Figure 1). The pyridine groups are utilized for the metal coordination site to form the metallosupramolecular strands, which can be intertwined through the amidinium−carboxylate salt bridges to give rise to the double-stranded metallopolymers $\mathbf{3^{R}}$ and $\mathbf{3^{S}}$, as illustrated in Figure 1. In this paper, we describe the synthesis and characterization of the first double-stranded metallosupramolecular helical polymers with a controlled helicity along with their atomic force microscopy (AFM) visualization.

Supramolecular polymerization of the duplexes $\mathbf{1^{R}\cdot 2}$[7] and $\mathbf{1^{S}\cdot 2}$[7] with *cis*-diphenylbis(dimethyl sulfoxide)platinum(II)[8] (*cis*-$PtPh_2(DMSO)_2$) was first investigated by ^1H NMR spectroscopy (Figure 2). Upon mixing $\mathbf{1^{R}\cdot 2}$ and 2 equiv of *cis*-$PtPh_2(DMSO)_2$ in 1,1,2,2-tetrachloroethane-d_2 (TCE-d_2), the ^1H NMR spectrum of the mixture became significantly broadened and showed a signal due to free DMSO at 2.51 ppm, indicating that the supramolecular polymerization has occurred. The resonances of the NH protons remained at a low magnetic field of ca. 13.5 ppm,[3] showing that the salt bridges were retained after the polymerization.

To assess the hydrodynamic dimensions of the supramolecular polymers, DOSY ^1H NMR (diffusion-ordered spectroscopy) and DLS (dynamic light scattering) experiments were carried out at 25 °C in TCE.[7] The diffusion constants for $\mathbf{1^{R}\cdot 2}$ and $\mathbf{3^{R}}$ in TCE-d_2 were measured by pulsed field gradient NMR experiments using the BPPSTE pulse sequence.[9] The diffusion constant for the supramolecular polymer $\mathbf{3^{R}}$ was determined to be $D = 6.0 \times 10^{-11}$ m^2 s^{-1}, while a higher value of $D = 1.6 \times 10^{-10}$ m^2 s^{-1} was obtained for the monomer $\mathbf{1^{R}\cdot 2}$. These values mean that the hydrodynamic volume of $\mathbf{3^{R}}$ is ca. 20 times higher than that of $\mathbf{1^{R}\cdot 2}$.[10] The average hydrodynamic radius of $\mathbf{3^{R}}$ derived from the DLS data was $R_H =$ 9.5 nm.[7] The DLS and DOSY experiments were also carried out at different ratios of *cis*-$PtPh_2(DMSO)_2$ to $\mathbf{1^{S}\cdot 2}$; the assembly size reached its maximum at a ratio of 2.0, that is, the stoichiometry used for the supramolecular polymerization (Figure S7).[7] In contrast, the light scattering signals for $\mathbf{1^{R}\cdot 2}$ were undetectable. Thus, these results support the polymeric structure of $\mathbf{3^{R}}$.

Figure 1. The synthesis of the double-stranded metallosupramolecular helical polymers $\mathbf{3^{R}}$ and $\mathbf{3^{S}}$. $R^1 =$ (*R*)-1-phenylethyl for $\mathbf{1^{R}\cdot 2}$ and $\mathbf{3^{R}}$; (*S*)-1-phenylethyl for $\mathbf{1^{S}\cdot 2}$ and $\mathbf{3^{S}}$.

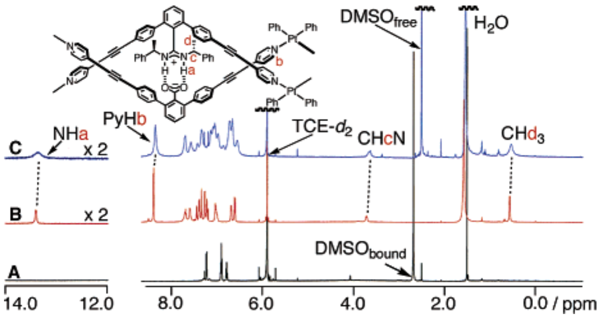

Figure 2. ^1H NMR spectra of (A) *cis*-$PtPh_2(DMSO)_2$ (1.0 mM), (B) $\mathbf{1^{R}\cdot 2}$ (1.0 mM), and (C) a polymerization mixture of $\mathbf{1^{R}\cdot 2}$ (1.0 mM) and *cis*-$PtPh_2(DMSO)_2$ (2.0 mM) in TCE-d_2 at 25 °C.

More information on the structures of the metallosupramolecular polymers was obtained by absorption and CD spectroscopies (Figure 3). The absorption spectrum of $\mathbf{3^{R}}$ in TCE showed a typical metal-to-ligand charge transfer (MLCT) band in the long wavelength regions (370−450 nm), and a marked bathochromic shift ($\Delta\lambda =$ ca. 15 nm) was observed for the absorption of ca. 320 nm when compared to the monomer $\mathbf{1^{R}\cdot 2}$, providing strong evidence for the Pt−N coordination leading to the large π-conjugation system of $\mathbf{3^{R}}$.[11] In addition, $\mathbf{3^{R}}$ and $\mathbf{3^{S}}$ exhibited perfect mirror image Cotton effects of each other, thus reflecting the absolute configurations of the (*R*)- and (*S*)-phenylethyl groups at the amidine residues, respectively. It should be mentioned that, in the CD spectra of $\mathbf{3^{R}}$ and $\mathbf{3^{S}}$, distinct Cotton effects were observed around the MLCT band regions, suggesting that the chirality of the phenylethyl groups

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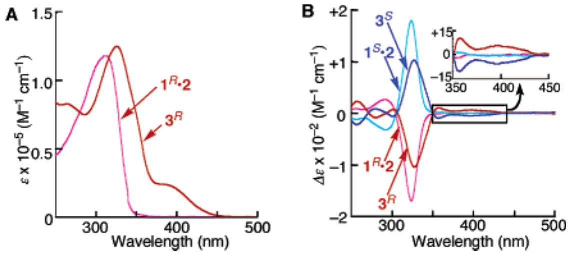

Figure 3. (A) Absorption and (B) CD spectra of $\mathbf{1}^{R}\cdot\mathbf{2}$, $\mathbf{1}^{S}\cdot\mathbf{2}$, $\mathbf{3}^{R}$, and $\mathbf{3}^{S}$ in TCE (1.0 mM) at ca. 25 °C.

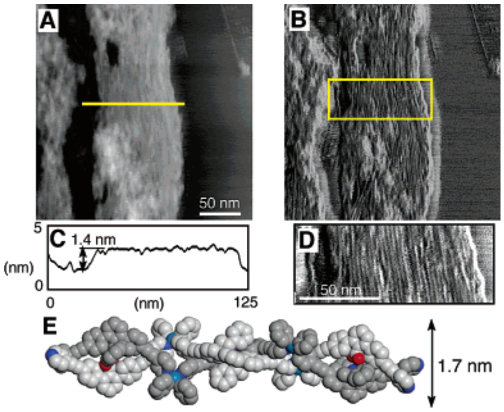

Figure 4. AFM (A) height and (B) phase images of $\mathbf{3}^{R}$ prepared by casting a dilute solution (4 μg mL^{-1}) in TCE on HOPG. (C) The cross-section profile along the yellow line in the image (A). (D) The magnified image corresponding to the area indicated by the square in the image (B). (E) A space-filling drawing of a possible right-handed double helical structure of the trimer of $\mathbf{3}^{R}$ obtained by MM calculation.[7]

is transferred to the Pt(II) complex moieties, and accordingly, the double-stranded metallopolymers $\mathbf{3}^{R}$ and $\mathbf{3}^{S}$ adopt an excess one-handed helical structure in solution.[12]

AFM provided direct evidence for the polymeric structure of $\mathbf{3}^{R}$. Panels A−D of Figure 4 show typical tapping-mode AFM images of $\mathbf{3}^{R}$ cast from a dilute solution in TCE ([$\mathbf{3}^{R}$] = 2 μM) on highly oriented pyrolytic graphite (HOPG). The AFM images showed that the polymers self-assembled into regular two-dimensional bundles with a constant height of 1.4 nm.[13] In the high-resolution AFM image (Figure 4D), the bundle structures were resolved into individual polymeric $\mathbf{3}^{R}$ chains packed parallel to each other with a chain−chain spacing of ca. 2.6 nm. Although we could not identify the helical structure of $\mathbf{3}^{R}$, these AFM observations are in good agreement with the molecular mechanics (MM)-calculated structure of $\mathbf{3}^{R}$ (Figure 4E).[14] The average length of the polymers was approximately 100 nm, corresponding to ca. 40 repeating units.

In summary, we have successfully synthesized the first artificial double-stranded metallosupramolecular helical polymers consisting of two complementary metallopolymer strands that are intertwined through chiral amidinium−carboxylate salt bridges. We believe that the combination of salt bridges and metal coordination used in this study can be applied to the construction of a wide variety of multiple-stranded supramolecules, which is now under investigation in our laboratory.

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Supporting Information Available: Experimental procedures for the synthesis and characterization of the duplexes $\mathbf{1}^{R}\cdot\mathbf{2}$ and $\mathbf{1}^{S}\cdot\mathbf{2}$, and double-stranded helical polymers $\mathbf{3}^{R}$ and $\mathbf{3}^{S}$. This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) The Cotton effect intensities of $\mathbf{3}^{R}$ and $\mathbf{3}^{S}$ showed almost no temperature dependency between +25 and −10 °C.

(12) We measured the CD spectra of the supramolecular polymers prepared at different ratios of *cis*-PtPh$_2$(DMSO)$_2$ to $\mathbf{1}^{S}\cdot\mathbf{2}$; the CD intensity at the MLCT region also showed a maximum value at a ratio of 2.0 (Figure S7B). We also performed a competition experiment using acetic acid as the competitor, which can unravel the duplex, but is inert to the Pt−pyridine coordination. Upon the addition of acetic acid to the solution of $\mathbf{3}^{S}$, the CD intensity decreased considerably (Figure S8A) because the duplex appeared to unravel.[7] In addition, the Cotton effects around the MLCT region disappeared completely, while the average hydrodynamic radius of the mixture hardly changed in the presence of excess acetic acid (Figure S8B). These results also support the double helical structure of the assembly assisted by salt bridges and metal coordination (Figure 1).

(13) In contrast, no fibrous structure could be found in the AFM images of the samples prepared by casting a solution of $\mathbf{1}^{R}\cdot\mathbf{2}$, but rather only globular objects were observed.[7]

(14) The helical $\mathbf{3}^{R}$ may have a right-handed double helix with an excess one-handedness on the basis of the X-ray structure of an analogous double helical oligomer of $\mathbf{1}^{R}\cdot\mathbf{2}$[3] and the MM calculation results together with the temperature-independent changes in the Cotton effect intensity of $\mathbf{3}^{R}$.

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