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ARTICLE

Unexpected Right-Handed Helical Nanostructures Co-Assembled from L-Phenylalanine Derivatives and Achiral Bipyridines

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Guofeng Liu,[ab] Linyi Bai,[b] Jinying Liu,[a] Chuanliang Feng*[a] and Yanli Zhao*[bc]

The construction of chiral supramolecular systems with desirable handedness is of great importance in materials science, chemistry and biology, since chiral nanostructures exhibit fascinating photophysical properties and unique biological effects. Herein, we report that achiral bipyridines can co-assemble with L-phenylalanine derivatives into unexpected right-handed helical nanostructures rather than left-handed helix by utilizing intermolecular hydrogen bonding interactions formed between the pyridyl and carboxylic groups. This work opens up a route to develop chiral nanostructures with desirable handedness through the co-assembly of simple molecular building blocks and provides a straightforward insight into the chirality control of nanostructures in supramolecular systems.

Introduction

Chiral supramolecular architectures assembled from small molecular building blocks have been attracting extensive interests owing to their controllable structural features, their relationship to biological structures, and potential applications in chiral recognition and separation.[1] Although numerous helical or twisted nanostructures and ordered ensembles have been successfully produced by molecular self-assembly from either single or multiple molecular components for utilizations in chemistry,[2] biology[3] and materials science,[4] it has still remained challenging to construct chiral nanostructures with desirable conformation (*i.e.*, right-handed, *P*; left-handed, *M*) from specific chiral building blocks at will. On the other hand, in comparison with the rich knowledge that has been gathered with regard to establishing chiral nanostructures from either chiral or achiral building blocks,[5] rare studies have reflected explicit relationship between the chirality of nanoarchitectures and enantiomeric monomers.[6] Obviously, gel-phase materials are a key test-bed for understanding the impact of molecular chirality on nanoscale self-assembly or co-assembly, since supramolecular chirality of gels can be finely tuned by both the chirality of component molecules[7] and special spatial arrangements of building blocks.[8] After a detailed survey of previous literature reports, it was wondrously found that left-handed twist or helix is often co- or self-assembled from *L*-form amino acid based molecular building blocks, while right-handed twist or helix is normally aggregated from *D*-type counterparts.[9] There are some reports of right-handed twist or helix co-assembled from *L*-type amino acid based building blocks.[8c, 10] Thus, how to fine tailor the building blocks aggregating into a desirable specific motif remains in its infancy.

It is important to gain further insights into the fundamentals of chiral transfer and expression in the co-assembled hydrogel systems, which will enable us to obtain a comprehensive understanding of the design of new chiral materials and to fine tune the chirality of the co-assemblies. Herein, uniform right-handed helical nanostructures were obtained from the co-assembly of various achiral bipyridine derivatives with two chiral gelators (LPF and LCHF) derived from L-phenylalanine through strong intermolecular hydrogen bonding formed between achiral bipyridines and L-type enantiomers (Fig. 1).

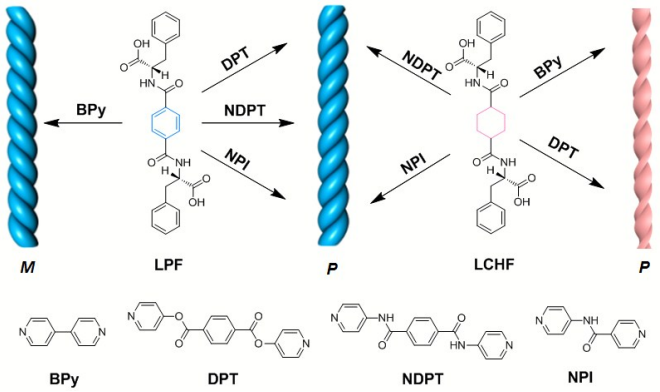

Fig. 1 Schematic illustration of chiral nanostructures co-assembled from *L*-type enantiomeric monomers (LPF and LCHF) with achiral bipyridines (BPy, DPT, NDPT, and NPI). *M* and *P* denote left- and right-handed helical nanostructures, respectively.

Results and discussion

[a] State Key Lab of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai, 200240, China. E-mail: clfeng@sjtu.edu.cn
[b] Division of Chemistry and Biological Chemistry, School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, 637371, Singapore. E-mail: zhaoyanli@ntu.edu.sg
[c] School of Materials Science and Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

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Unexpected right-handed helical nanostructures of hydrogels

Molecules LPF and LCHF, based on 1,4-phenyldicarboxamide and 1,4-cyclohexanedicarboxamide respectively, contain a helicogenic *L*-phenylalanine motif, and carry a COOH group at each terminus of the two phenylalanine arms. Hence, they are bistopic ligands. To co-assemble them into hydrogels, we rationally designed four bistopic bipyridine ligands (BPy, DPT, NDPT, and NPI) by utilizing hydrogen-bonding interactions between the pyridyl nitrogen atom and H-O group of carboxylic acid.[11] The synthesis of LCHF, DPT, and NPI is outlined in the experimental section, and BPy is commercially available. LPF and NDPT were synthesized according to a previous report.[8c] All the newly synthesized compounds were fully characterized by NMR spectroscopy and high-resolution mass spectrometry (Fig. S1-S14).

The ability of four achiral bipyridines (BPy, DPT, NDPT, and NPI) to co-assemble with equimolar LPF or LCHF was first determined by the formation of hydrogels by means of heating-to-cooling and inversion tests (Fig. S15). LPF+DPT, LPF+NPI, LPF+BPy and LPF+NDPT formed stable homogeneous hydrogels in the vials. Scanning electronic microscopy (SEM) images of diluted samples of the gels on silicon wafer showed enantiomerically enriched, helical ribbon fibers (Fig. 2 and S16-S23). All the co-assembled hydrogels (Fig. 2a-d) are organized into ropelike fibers with the helicity pitches around hundreds of nanometers. In Fig. 2a, the fibers from the LPF+BPy gel exhibited exclusively left-handed (M-type) helicity with a diameter in hundreds of nanometers. Surprisingly, fibers from LPF+DPT, LPF+NPI, and LPF+NDPT (Fig. 2b-d) all displayed beautiful uniform right-handed (P-type) helix with a diameter in tens of nanometers, which are absolutely opposite with the chirality of the LPF+BPy gel. According to previous reports,[3a,9a-c] specific one-dimensional nanofibers self-assembled from L-phenylalanine derived monomers usually exhibit exact left-handedness.

To explore if this unexpected phenomenon is also applicable to other gel systems, microscopic nanostructures assembled from achiral bipyridines with LCHF were investigated in detail. Intriguingly, uncommon right-handed helical nanofibers with nearly the same helicity pitches around hundreds of nanometers were observed in the SEM images of all hydrogels (Fig. 2e-h). This is a bit different with LPF based gel systems, where LPF+BPy exhibited exclusively left-handed (M-type) helicity. But, right-handed nanofibers were observed from LCHF+BPy. On the basis that the only difference in LCHF+BPy is the central benzene ring of LPF instead of the cyclohexyl core of LCHF, it was anticipated that the chirality of supramolecular aggregates could be tuned by only changing some functional groups rather than altering inherent chirality of enantiomeric monomers. In addition, these studies indicate how a slight change in molecular structure of the building blocks dramatically influences the overall chirality of supramolecular aggregates in two-component hydrogels. The chirality of assemblies shown here is not only strongly determined by the chiral center of phenylalanine units in LPF and LCHF, but also highly affected by molecular structure of achiral bipyridines, both of which collectively play vital roles in rigidifying the aggregates and guiding them to form unique chiral hydrogels.

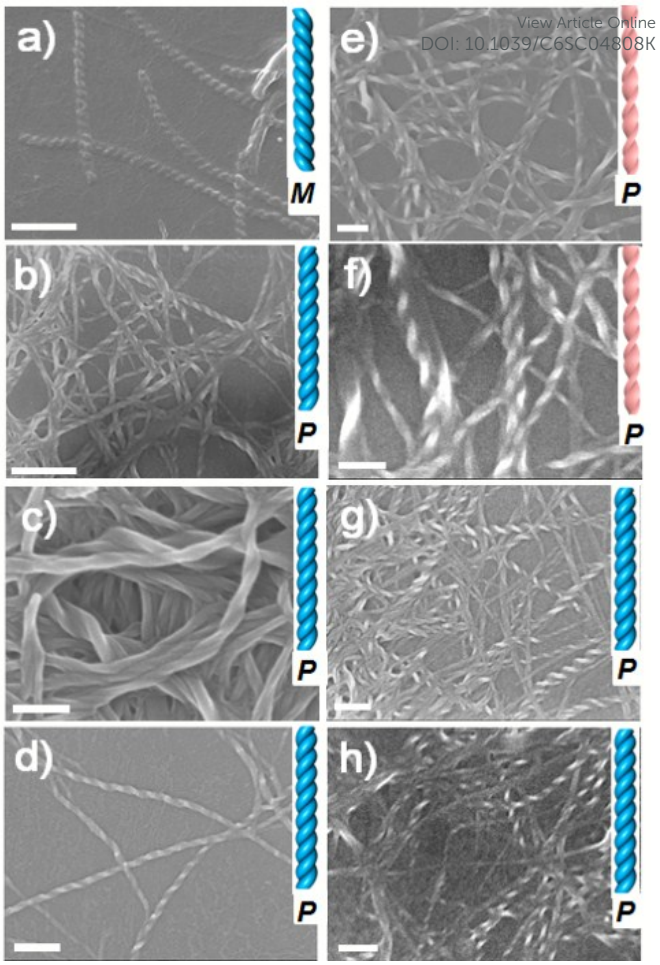

Fig. 2 SEM images of supramolecular hydrogels based on LPF or LCHF co-assembled with achiral bipyridines. a) LPF+BPy, b) LPF+DPT, c) LPF+NDPT, d) LPF+NPI, e) LCHF +BPy, f) LCHF +DPT, g) LCHF +NDPT, and h) LCHF +NPI. Scale bars: 5 μm for a), 500 nm for b), and 200 nm for c-h).

CD activity of co-assembled hydrogels

To gain further insight into these helical supramolecualr structures, circular dichroism (CD) spectra of the co-assembled hydrogels were measured at room temperature (Fig. 3 and S24). The CD spectra of hydrogels LPF+NPI, LPF+DPT and LPF+BPy all exhibited a negative dichroic signal at around 205 nm, assigning to intramolecular π-π* transitions in the peripheral phenyl group of LPF.[8c] Interestingly, for hydrogels of LPF+BPy, its CD spectrum also showed a negative Cotton effect at 268 nm (Fig. 3A), whereas for LPF+DPT, LPF+NDPT, and LPF+NPI hydrogels, a positive dichroic signal was shown at 235 nm, 293 nm, and 265 nm respectively, which was assigned to intramolecular transitions from the amide linkage to the central aryl group according to our previous calculations on LPF.[8c] Compared with hydrogels of LPF+BPy, a chiral transition into opposite optically active hydrogels (LPF+DPT, LPF+NDPT, and LPF+NPI) was obtained only by changing achiral components (BPy, DPT, NDPT, and NPI), which was in good correlation with the helical microscopic structures observed in the SEM images. In addition, the contribution of linear dichroism (LD) on the CD signals was

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investigated. As shown in Fig. S25, the intensity of LD signals was much lower than that of corresponding CD signals (except for LPF+NPI), indicating that the LD contribution could be negligible in these gels. In the case of LPF+NPI hydrogel, in order to get rid of the LD influence, the hydrogel film was placed in different angles and an average CD signal (Fig. S26) was taken as reported in literature.[12]

Thus, the relationship between the handedness of the helical fibers and CD signals could be obtained. The M-type LPF+BPy co-assembly exhibits a negative Cotton effect at 268 nm, whereas P-type supramolecular structures in LPF+DPT, LPF+NDPT, and LPF+NPI show a positive dichroic signal (Fig. 3A). It is worth to note that all of the hydrogels possess the same S-type stereocenter within peripheral L-phenylalanine units. Thus, their CD spectra should not be exact mirror images. Nevertheless, the chirality of these supramolecular assemblies and their chiroptical activities could be inversed by altering achiral bipyridines. For LCHF systems, all the CD spectra (Fig. 3B) of hydrogels (LCHF+BPy, LCHF+DPT, LCHF+NDPT, and LCHF+NPI) exhibited positive dichroic signals around 200 nm and among 250-283 nm from the amide linkage, which are in good agreement with the right-handed helical nanofibers observed in SEM images (Fig. 2e-h). The enantiomer of LCHF, i.e., DCHF was also synthesized as a control. Corresponding spectra of LCHF and DCHF were determined (Fig. S27 and S28), showing perfect mirror imaging profiles.

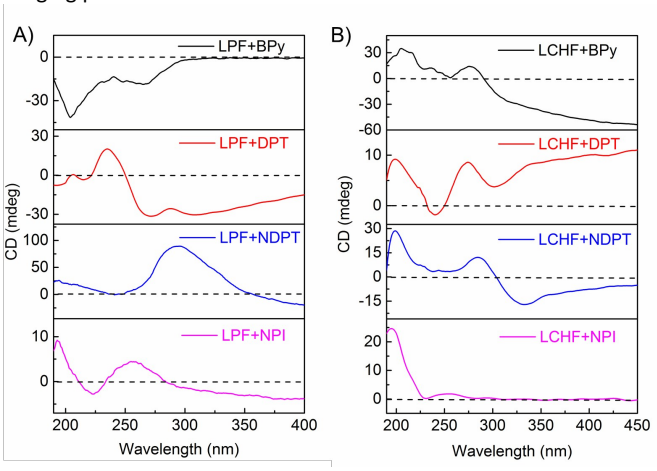

Fig. 3 CD spectra of hydrogels for (A) LPF+BPy, LPF+DPT, LPF+NDPT, and LPF+NPI, and (B) LCHF+BPy, LCHF+DPT, LCHF+NDPT, and LCHF+NPI.

On account of the same L-type phenylalanine stereocenter within the LPF and LCHF components and achiral bipyridines used, it was reasonably inferred that the changes of CD signals and unexpected enantiomerically enriched helical nanostructures observed from SEM images could be attributed to specific stacking modes of co-assembling building blocks, which bring vital effects on chiroptical behavior and chiral morphology of hydrogels by strong and extensive intermolecular hydrogen bonding between L-phenylalanine derivatives and achiral bipyridines.

Co-assembly mechanism of hydrogels

The co-assembling mechanism of these hydrogels was further investigated by Fourier transform infrared (FTIR), because FTIR measurements (Fig. 4 and S29-S35) can provide valuable information about the interaction of supramolecular aggregates at molecular level. The as-prepared xerogel of LPF was first characterized by FTIR, showing well-defined amide I bands centered at 1621 cm^{-1}, amide II bands centered at 1551 cm^{-1} and stretching vibration bands of C=O from carboxyl groups at 1738 cm^{-1} (Fig. 4 and S31). These bands shifted in homogeneous dichloromethane solution (Fig. S31 and Table S1). These observations suggest well-developed hydrogen bonding networks formed through the amide and carboxylic acid units in the self-assembled nanofibers. FTIR spectrum (Fig. S32) of LPF+BPy gels clearly displayed well-defined amide I and II bands centered at 1636 cm^{-1} and 1543 cm^{-1} respectively, indicating that the amide groups participate in strong hydrogen bonds. In comparison with LPF xerogel, new bands at 2453 and 1951 cm^{-1} and the band decrease at 1713 cm^{-1} clearly suggest the formation of carboxylic acid-pyridyl hydrogen bonds in LPT+BPy. Moreover, the appearance of a peak due to N-H stretching vibration at 3308 cm^{-1} further evidenced the complicated nature of hydrogen bonds. Similarly, FTIR spectra of LPF+DPT, LPF+NPI, and LPF+NDPT xerogels all showed well-defined amide I and II bands centered around 1635 and 1540 cm^{-1} respectively, and the stretching vibration bands of C=O from carboxylic groups at 1735 cm^{-1} disappeared coupled with a new peak at ~1695 cm^{-1}. In addition, two peaks assigned to O-H stretching vibrations at 2495 and 1950 cm^{-1} were observed. FTIR studies confirm that these co-assembled hydrogel frameworks are stabilized by intermolecular hydrogen bonding interactions between amide/pyridine units and carboxylic acid groups.

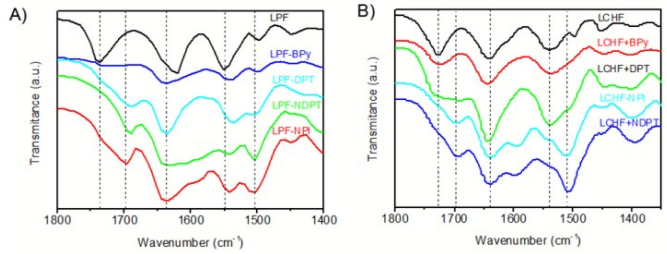

Fig. 4 FTIR spectra of xerogels self- or co-assembled from LPF (A) and LCHF (B).

For LCHF based hydrogel systems (Fig. S33 and S34), compared with LCHF gel exhibiting carboxylic band at 1726 cm^{-1} ($\nu_{C=O}$ of COOH), the carboxylic band of LCHF+BPy gel was observed at 1722 cm^{-1}, and a new peak occurred at 2527 cm^{-1} due to O-H stretching vibrations was inferred from newly formed hydrogen bonding interaction between pyridinyl and carboxylic acid groups. For xerogels of LCHF+DPT, LCHF+NDPT, and LCHF+NPI, amide I bands shifted to 1691, 1694 and 1697 cm^{-1}, respectively. Well-defined amide II bands (δ_{N-H} of CONH) at 1537 cm^{-1} in LCHF powder shifted to 1535 cm^{-1} for LCHF+BPy, 1537 cm^{-1} for LCHF+DPT, 1506 cm^{-1} for LCHF+NDPT, and 1510 cm^{-1} for LCHF+NPI. In addition, new peaks due to O-H stretching vibrations were observed at 2546 and 1951 cm^{-1} for LPF+DPT, 2566 and 1945 cm^{-1} for LPF+NDPT, and 2503 and 1953 cm^{-1} for LPF+NPI. Thus, the co-assembled hydrogels based on LCHF were also driven by intermolecular hydrogen bonds between amide/pyridine units and carboxylic acid groups.

On the basis of all the results discussed above, it can be concluded that the main driving forces for the co-assemblies are two types of intermolecular hydrogen bonds. Firstly, strong hydrogen bond is formed between pyridyl nitrogen and the hydroxy group of a carboxylic acid, which drives the building blocks to co-assemble in a head-to-tail fashion. Second, three-dimensional fiber networks are obtained through the formation of hydrogen bonds between amide groups. These two kinds of intermolecular hydrogen bonds stabilize the co-assembled hydrogel frameworks.

VCD activity of co-assembled hydrogels

The chiroptical activities of these hydrogels were also studied by vibrational circular dichroism (VCD).[13] We conducted the VCD measurements by coating hydrogels on CaF_2 wafer and then dried under infrared lamp. For LPF based hydrogel systems (Fig. 5A), LPF+BPy exhibited a (-/+) VCD signal of the C=O stretching band among 1750-1600 cm^{-1}, whereas the VCD signal of the band switched to a significant (+/-) pattern for LPF+DPT, LPF+NDPT, and LPF+NPI hydrogels. Thus, a strong and extensive C=O···H-N hydrogen-bonding network significantly stabilizing the co-assembled supramolecular hydrogels is inferred from vibrational amide I stretching band at around 1636 cm^{-1}. This amide I VCD band in LPF+BPy gives a (-/+) pattern, and that in LPF+DPT, LPF+NDPT and LPF+NPI shows an opposite (+/-) signal. The VCD patterns imply the inversion of the chirality from LPF+BPy to LPF+DPT/LPF+NDPT /LPF+NPI at room temperature. Surprisingly, all of these VCD bands revealed a (-/+) pattern in LCHF based co-assembled hydrogels among 1750-1600 cm^{-1}, which may be ascribed to different central cyclohexyl unit in LCHF (Fig. 5B).

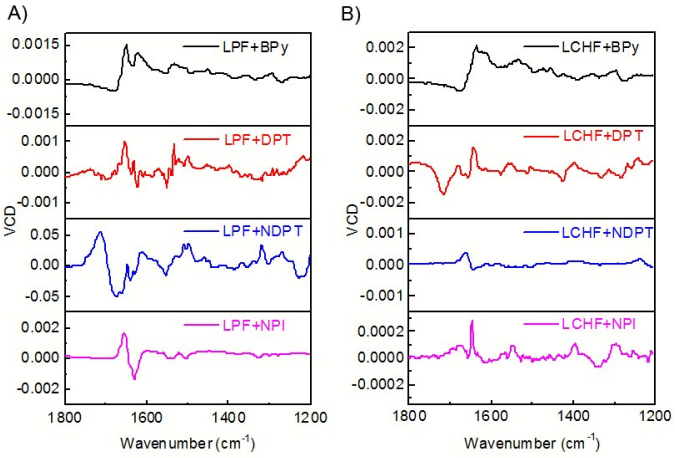

Fig. 5 VCD spectra of (A) LPF+BPy, LPF+DPT, LPF+NDPT, and LPF+NPI hydrogels, and (B) LCHF+BPy, LCHF+DPT, LCHF+NDPT, and LCHF+NPI hydrogels.

Since all of the samples have the same S-type stereocenter within the L-phenylalanine units, dissimilar VCD behavior between LPF+BPy gel and LPF+DPT/LPF+NDPT/LPF+NPI gels suggests that their supramolecular self-assembly could result in the formation of distinct aggregates with opposite handedness by using different achiral counterparts. The present results already indicate that LPF can assemble into different enantiomerically enriched helical supramolecular structures with achiral bipyridines. In this very rare two-component supramolecular hydrogel system, unexpected right-handed nanostructures (except for LPF+BPy) were successfully constructed by the co-assembly of L-phenylalanine derivatives with achiral bipyridines, strongly revealing that the supramolecular chirality of nanostructures is not only determined by the chirality of monomers (LPF and LCHF), but also highly influenced by the stacking mode of building blocks through strong and extensive intermolecular hydrogen bonding during the co-assembling process. On the basis of these results, it can be confirmed that the intermolecular hydrogen bonding from COOH-pyridine and amide-amide leads to different interaction modes of LPF and LCHF with achiral bipyridines. These two types of intermolecular hydrogen bonding interactions could possibly enable the building blocks to assemble into uniform helical aggregates.

Conclusions

In conclusion, unexpected right-handed helical nanostructures have been successfully constructed by the co-assembly of L-phenylalanine derivatives with achiral bipyridines in a two-component supramolecular approach. In this way, we were able to demonstrate that the chirality of supramolecular architectures could be determined by both the molecular chirality and the stacking mode of building blocks in the co-assembly process. Studying a series of right-handed helical nanofibers containing building blocks with the same L-type chiral stereocenter and achiral bipyridines with different molecular conformation has enabled us to gain insight into the conveyance of configurational information during helical nanostructure formation. With the generality of this approach demonstrated for a number of different building block combinations, we expect that this approach should be applicable to a broad variety of building blocks for promoting the establishment of chiral nanomaterials with desirable topologies. Further investigations using this strategy to define chiral relationship between enantiomeric monomers and supramolecular assemblies would bring new insights into deeper understanding of chiral assembly process and regulating supramolecular aggregation.

Experimental

General

The NMR spectra were recorded on a Bruker Advance III 300 Instrument (300 MHz). HRMS were determined on a Water Q-Tof Mass Instrument. Amino-4-pyridine, 1,4-benzene-dicarbonyl dichloride, 4,4'-bipyridine, 4-carboxylicpyridine, 1,4-cyclohexane dicarboxylic acid, 4-dimethylaminopyridine (DMAP), 1-ethyl-3-(3-dimethylamino propyl)carbodiimide hydrochloride (EDCI), 4-hydroxypyridine, L-phenylalaninemethylester hydrochloride, thionyl chloride, and triethylamine (Et_3N) were purchased from Aladdin Chemicals.

Synthesis of LCHF

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1,4-Cyclohexanedicarboxylic acid (1.73 g, 10.00 mmol) was added to dry dichloromethane containing thionyl chloride (20 mL), and the mixture was stirred at 100 °C for 4 h. All the solvents were evaporated under vacuum and the residue liquid was collected to give 1,4-cyclohexanedicarbonyl dichloride. 1,4-Cyclohexane dicarbonyldichloride (2.0 g, 9.66 mmol) in dry dichloromethane (100 mL) was added dropwise to a dichloromethane solution (100 mL) containing *L*-phenylalaninemethyl ester hydrochloride (5.0 g, 23.18 mmol) and triethylamine (3.6 mL, 26.00 mmol) in an ice-water bath. After completing the addition, the solution was stirred at room temperature overnight. All the solvents were evaporated under vacuum and the residue was subsequently dissolved in dichloromethane (100 mL). After extraction by water, the organic phase was dried by anhydrous $MgSO_4$ and collected to give the dimethyl ester of LCHF (LCHF-OMe, 4.60 g, 9.30 mmol, 84%). ^{1}H NMR (300 MHz, DMSO-d_6, ppm): δ = 1.43 (t, 4H, CH_2), 1.86 (m, 4H, CH_2), 2.05 (s, 2H, CH), 3.11 (dd, 4H, CH_2), 3.71 (s, 6H, CH_3), 4.87 (d, 2H, CH), 5.92 (d, 2H, CO-NH), 7.07 (m, 4H, Ar-H), 7.27 (d, 6H, Ar-H). ^{13}C NMR (101 MHz, DMSO-d_6, ppm): δ = 174.96, 172.34, 136.03, 128.76, 127.36, 125.47, 52.96, 52.54, 44.49, 38.04, 28.78, 28.49.

For the hydrolysis, aqueous NaOH (10 mL, 2.0 M) was added to a cooled suspension of LCHF-OMe (5.43 g, 6.14 mmol) in MeOH (20 mL). The mixture was slowly warmed up to room temperature and stirred for 24 h, and a clear solution was obtained. The solution was then acidified with 3.0 M HCl until pH value was no more than 3.0, and gel-like precipitate was formed. The gel phase was filtered, washed with deionized water, and finally dried in the vacuum oven to give LCHF (3.0 g, 6.38 mmol, 69.2%). Overall yield of LCHF: 66.6%. ^{1}H NMR (300 MHz, DMSO-d_6, ppm): δ = 12.66 (s, 2H, COOH), 8.06 (d, 2H, CONH), 7.30 (m, 10H, Ar-H), 4.45 (s, 2H, CH), 2.98 (m, 4H, CH_2), 2.10 (s, 2H, CH), 1.63 (d, 4H, CH_2), 1.24 (d, 4H, CH_2). ^{13}C NMR (75 MHz, DMSO-d_6, ppm): δ = 174.31, 172.70, 137.52, 128.90, 127.89, 126.16, 53.42, 43.33, 37.20, 28.66. EI-MS for $C_{26}H_{30}O_6N_2$ calcd. 466.2104; found 467.2180 $[M+H]^+$.

Synthesis of DPT

1,4-Bnzenedicarbonyl dichloride (1.01 g, 4.98 mmol) in dry dichloromethane (10 mL) was added dropwise to a dichloromethane solution (20 mL) containing 4-hydroxypyridine (1.42 g, 14.93 mmol), EDCI (2.24 g, 11.94 mmol) and DMAP (0.06 g, 0.50 mmol). The solution was stirred at room temperature for 12 h. After filtration, all the solvents were evaporated under vacuum. The residue was washed with deionized water, and finally dried in the vacuum oven to give solid DPT (0.96 g, 3.00 mmol, 60.2 %). ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ = 8.71-8.72 (d, 4H, Ar-H), 8.35 (s, 4H, Ar-H), 7.26-7.29 (dd, 4H, Ar-H). ^{13}C NMR (100 MHz, DMSO-d_6, ppm): δ = 176.77, 167.36, 140.24, 135.28, 129.82, 116.49. EI-MS (m/z) for $C_{18}H_{14}N_2O_4$ calcd. 320.0797; found 321.0869 $[M+H]^+$.

Synthesis of NPI

4-Carboxylicpyridine (0.61 g, 4.95 mmol) in dry dichloromethane (10 mL) was added dropwise to a dichloromethane solution (20 mL) containing amino-4-pyridine (0.75 g, 7.97 mmol), EDCI (0.99 g, 5.16 mmol) and DMAP (0.04 g, 0.33 mmol). The solution was stirred at room temperature for 12 h. After filtration, all the solvents were evaporated under vacuum. The residue was washed with deionized water, and finally dried in the vacuum oven to give claybank solid NPI (0.23 g, 1.15 mmol, 23.3 %). ^{1}H NMR (400 MHz, DMSO-d_6, ppm): δ = 7.78-7.80 (d, 2H, Ar-H), 7.87-7.89 (d, 2H, Ar-H), 8.52-8.53 (d, 2H, Ar-H), 8.82-8.84 (d, 2H, Ar-H), 10.84 (s, 1H, CO-NH). ^{13}C NMR (100 MHz, DMSO-d_6, ppm): δ = 166.64, 150.70-150.92, 147.60, 143.60, 122.93, 115.65. EI-MS (m/z) for $C_{11}H_9N_3O$ calcd. 199.0746; found 200.0811 $[M+H]^+$.

Hydrogel preparation

The LPF+DPT hydrogel with 0.2 wt % LPF+DPT is used as an example to describe the preparation procedure. LPF+DPT (2.0 mg/mL, equimolar mixture of LPF and DPT) was suspended in a septum-capped 5.0 mL glass vial and heated until a homogeneous solution was obtained. The solution solidified into a hydrogel after standing for a half-hour at room temperature.

Scanning electron microscopy (SEM)

SEM was performed on a JEOL JSM-7600F microscope with an accelerating voltage of 5 kV. Before SEM measurements, samples were prepared by depositing dilute solutions of gels on silicon wafers, followed by drying and coating them with a thin layer of Pt to increase the contrast.

Circular dichroism (CD) spectra

CD spectra were obtained using JASCO J-1500 CD spectrometer with bandwidth of 1.0 nm. CD spectra of hydrogels were recorded in the UV region (190-400 nm) using a 0.1 mm quartz cuvette with the total gelator concentration at 0.2 wt %.

Fourier transform infrared (FTIR) spectra

FTIR spectra of xerogels were taken using a Shimadzu FT-IR Instrument. The KBr disk technique was used for the solid-state measurements. Solution spectra were measured by dropping dichloromethane solution on KBr wafers and were corrected for solvent and cell absorption. The samples were scanned between the wavelengths of 4000 and 400 cm^{-1} at an interval of 1.9285 cm^{-1}.

Vibrational circular dichroism (VCD) spectra

VCD spectra were measured at BioTools, using a ChiralIR-2X Fourier transform VCD (FT-VCD) spectrometer equipped with an MCT detector and the Dual PEM option for enhanced VCD baseline stability. VCD spectra were recorded at a resolution of 4 cm^{-1} by co-adding 1000 scans. The gel samples (at a concentration of 2.0 mg/mL) were dried under infrared lamp after coating on CaF_2 wafer and held in a variable path length cell with CaF_2 windows.

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Notes and references

1. (a) T. Aida, E. W. Meijer and S. I. Stupp, *Science*, 2012, **335**, 813; (b) T. F. A. De Greef, M. M. J. Smulders, M. Wolffs, A. P. H. J. Schenning, R. P. Sijbesma and E. W. Meijer, *Chem. Rev.*, 2009, **109**, 5687; (c) A. R. Palmans and E. W. Meijer, *Angew. Chem., Int. Ed.*, 2007, **46**, 8948; (d) M. Liu, L. Zhang and T. Wang, *Chem. Rev.*, 2015, **115**, 7304; (e) L. Zhang, X. Wang, T. Wang and M. Liu, *Small*, 2015, **11**, 1025; (f) L. Zhang, T. Wang, Z. Shen and M. Liu, *Adv. Mater.,* 2016, **28**, 1044; (g) L. Zhu, X. Li, S. Wu, K. T. Nguyen, H. Yan, H. Ågren and Y. Zhao, *J. Am. Chem. Soc.*, 2013, **135**, 9174; (h) M. de Loos, J. van Esch, R. M. Kellogg and B. L. Feringa, *Angew. Chem., Int. Ed.*, 2001, **113**, 633.
2. (a) D. J. van Dijken, J. M. Beierle, M. C. Stuart, W. Szymanski, W. R. Browne and B. L. Feringa, *Angew. Chem., Int. Ed.*, 2014, **53**, 5073; (b) A. T. Haedler, S. C. Meskers, R. H. Zha, M. Kivala, H. W. Schmidt and E. W. Meijer, *J. Am. Chem. Soc.*, 2016, **138**, 10539; (c) M. M. J. Smulders, A. P. H. J. Schenning and E. W. Meijer, *J. Am. Chem. Soc.*, 2008, **130**, 606; (d) J. van Gestel, A. R. A. Palmans, B. Titulaer, J. A. J. M. Vekemans and E. W. Meijer, *J. Am. Chem. Soc.*, 2005, **127**, 5490; (e) T. E. Kaiser, V. Stepanenko and F. Wurthner, *J. Am. Chem. Soc.*, 2009, **131**, 6719.
3. (a) G. Liu, D. Zhang and C. Feng, *Angew. Chem., Int. Ed.*, 2014, **53**, 7789; (b) K. Lv, L. Zhang, W. Lu and M. Liu, *ACS Appl. Mater. Interfaces*, 2014, **6**, 18878.
4. (a) J. H. Jung, M. Masuda, T. Shimizu, and S. Shinkai, *J. Am. Chem. Soc.*, 2001, **123**, 8785; (b) J. H. Jung, H. Kobayashi, K. J. C. van Bommel, S. Shinkai and T. Shimizu, *Chem. Mater.*, 2002, **14**, 1445; (c) F. Rodríguez-Llansola, B. Escuder and J. F. Miravet, *J. Am. Chem. Soc.*, 2009, **131**, 11478; (d) Y. Yang, M. Suzuki, H. Fukui, H. Shirai and K. Hanabusa, *Chem. Mater.*, 2006, **18**, 1324.
5. (a) Z. Shen, T. Wang and M. Liu, *Angew. Chem., Int. Ed.*, 2014, **53**, 13424; (b) Z. Shen, Y. Jiang, T. Wang and M. Liu, *J. Am. Chem. Soc.*, 2015, **137**, 16109; (c) J. Yuan and M. H. Liu, *J. Am. Chem. Soc.*, 2003, **125**, 5051; (d) P. J. M. Stals, P. A. Korevaar, M. A. J. Gillissen, T. F. A. de Greef, C. F. C. Fitié, R. P. Sijbesma, A. R. A. Palmans and E. W. Meijer, *Angew. Chem., Int. Ed.*, 2012, **51**, 11297; (e) F. Garcia and L. Sanchez, *J. Am. Chem. Soc.*, 2012, **134**, 734; (f) A. Maity, M. Gangopadhyay, A. Basu, S. Aute, S. S. Babu and A. Das, *J. Am. Chem. Soc.*, 2016, **138**, 11113; (g) K. J. van Bommel, C. van der Pol, I. Muizebelt, A. Friggeri, A. Heeres, A. Meetsma, B. L. Feringa and J. van Esch, *Angew. Chem., Int. Ed.*, 2004, **43**, 1663.
6. (a) C. Roche, H. J. Sun, P. Leowanawat, F. Araoka, B. E. Partridge, M. Peterca, D. A. Wilson, M. E. Prendergast, P. A. Heiney, R. Graf, H. W. Spiess, X. B. Zeng, G. Ungar and V. Percec, *Nat. Chem.*, 2016, **8**, 80; (b) W. Edwards and D. K. Smith, *J. Am. Chem. Soc.*, 2014, **136**, 1116.
7. (a) A. Friggeri, C. van der Pol, K. J. C. van Bommel, A. Heeres, M. C. A. Stuart, B. L. Feringa and J. van Esch, *Chem.–Eur. J.*, 2005, **11**, 5353; (b) B. W. Messmore, P. A. Sukerkar and S. I. Stupp, *J. Am. Chem. Soc.*, 2005, **127**, 7992; (c) C. Li, Z. Tang and L. Jiang, *J. Am. Chem. Soc.,* 2010, **132**, 8202; (d) E. Yashima and K. Maeda, *Macromolecules*, 2007, **41**, 3; (e) Y. Yan, Z. Yu, Y. W. Huang, W. X. Yuan and Z. X. Wei, *Adv. Mater.*, 2007, **19**, 3353; (f) Q. Li, L. Green, N. Venkataraman, I. Shiyanovskaya, A. Khan, A. Urbas and J. W. Doane, *J. Am. Chem. Soc.*, 2007, **129**, 12908; (g) W. Makiguchi, S. Kobayashi, Y. Furusho and E. Yashima, *Angew. Chem., Int. Ed.*, 2013, **52**, 5275; (h) S. Liu, Y. Duan, X. Feng, J. Yang and S. Che, *Angew. Chem., Int. Ed.*, 2013, **52**, 6858; (i) A. R. Hirst, D. K. Smith, M. C. Feiters and H. P. M. Geurts, *Chem.–Eur. J.*, 2004, **10**, 5901; (j) D. Berthier, T. Buffeteau, J.-M. Léger, R. Oda and I. Huc, *J. Am. Chem. Soc.*, 2002, **124**, 13486; (k) J. H. K. K. Hirschberg, L. Brunsveld, A. Ramzi, J. A. J. M. Vekemans, R. P. Sijbesma and E. W. Meijer, *Nature*, 2000, **407**, 167; (l) R. Oda, I. Huc, M. Schmutz, S. J. Candau and F. C. MacKintosh, *Nature*, 1999, **399**, 566.
8. (a) D. K. Smith, *Chem. Soc. Rev.*, 2009, **38**, 684; (b) X. Wu, Y. Li, B. Li, X. Zhu, K. Hanabusa and Y. Yang, *J. Am. Chem. Soc.*, 2009, **131**, 5986; (c) G. Liu, L. Zhu, W. Ji, C. Feng and Z. Wei, *Angew. Chem., Int. Ed.*, 2016, **55**, 2411.
9. (a) Z. Sun, Z. Li, Y. He, R. Shen, L. Deng, M. Yang, Y. Liang and Y. Zhang, *J. Am. Chem. Soc.*, 2013, **135**, 13379; (b) G. Y. Qing, X. X. Shan, W. R. Chen, Z. Y. Lv, P. Xiong and T. L. Sun, *Angew. Chem., Int. Ed.*, 2014, **53**, 2124; (c) Y. Wang, W. Qi, R. Huang, X. Yang, M. Wang, R. Su and Z. He, *J. Am. Chem. Soc.*, 2015, **137**, 7869; (d) Y. Cai, Z. Guo, J. Chen, W. Li, L. Zhong, Y. Gao, L. Jiang, L. Chi, H. Tian and W. H. Zhu, *J. Am. Chem. Soc.*, 2016, **138**, 2219; (e) X. Wang, P. Duan and M. Liu, *Chem. Commun.*, 2012, **48**, 7501; (f) K. Lv, L. Qin, X. Wang, L. Zhang and M. Liu, *Phy. Chem. Chem. Phy.*, 2013, **15**, 20197; (g) C. Liu, Q. Jin, K. Lv, L. Zhang and M. Liu, *Chem. Commun.*, 2014, **50**, 3702; (h) Q. Jin, L. Zhang, X. Zhu, P. Duan and M. Liu, *Chem.–Eur. J.*, 2012, **18**, 4916; (i) V. Castelletto, I. W. Hamley, C. e. Cenker, U. Olsson, J. Adamcik, R. Mezzenga, J. F. Miravet, B. Escuder and F. Rodríguez-Llansola, *J. Phy. Chem. B*, 2011, **115**, 2107.
10. X. Zhu, P. Duan, L. Zhang and M. Liu, *Chem.–Eur. J.*, 2011, **17**, 3429.
11. (a) G. Liu, W. Ji, W. Wang and C. Feng, *ACS Appl. Mater. Interfaces*, 2015, **7**, 301; (b) G. Liu, W. Ji and C. Feng, *Langmuir*, 2015, **31**, 7122.
12. (a) A. Tsuda, M. A. Alam, T. Harada, T. Yamaguchi, N. Ishii and T. Aida, *Angew. Chem., Int. Ed.*, 2007, **46**, 8198; (b) M. Wolffs, S. J. George, Ž. Tomović, S. C. J. Meskers, A. P. H. J. Schenning and E. W. Meijer, *Angew. Chem., Int. Ed.*, 2007, **46**, 8203; (c) P. Guo, L. Zhang and M. Liu, *Adv. Mater.*, 2006, **18**, 177.
13. F. Aparicio, B. Nieto-Ortega, F. Najera, F. J. Ramirez, J. T. L. Navarrete, J. Casado and L. Sanchez, *Angew. Chem., Int. Ed.*, 2014, **53**, 1373.

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TOC

Achiral bipyridines can co-assemble with *L*-phenylalanine derivatives into unexpected right-handed helical nanostructures rather than left-handed helix by utilizing intermolecular hydrogen bonding formed between pyridyl and carboxylic groups.