

Retro-Diels–Alder-Triggered Supramolecular Polymerization of Tetrabenzoporphyrin into Pyramidal Aggregates

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Abstract: Supramolecular polymerization of π -extended compounds with hydrogen-bonding sites remains challenging, especially at high concentrations, due to their limited solubility in nonpolar solvents. Herein, we report a novel method incorporating a thermal precursor approach for the supramolecular polymerization of a poorly soluble tetrabenzoporphyrin (BP) derivative with multiple hydrogen-bonding sites and chiral cholesterol groups (**BP_{Chol}**). Polymerization in the nonpolar solvent tetralin is induced by the retro-Diels–Alder reaction of the highly soluble precursor (**CP_{Chol}**) to **BP_{Chol}** in the hot solution and subsequent natural cooling, as confirmed by monitoring absorption spectra. The emergence of circular dichroism signals corroborates the formation of aggregates with supramolecular chirality, as the first chiroptical characterization of BP aggregates. Detailed structural analysis using high-resolution microscopies reveals a unique pyramidal multilayer structure with a spiral nature. Additionally, faster cooling produces monolayer nanosheets, which differ from the multilayer structures formed upon natural cooling. This is due to a different nucleation process in the cooperative polymerization. By using the nanosheets as seeds, seed-induced polymerization is achieved, resulting in extended sheets. Notably, the indirect precursor method using **CP_{Chol}** enables outstanding polymerization at high concentrations (mM level) to afford micro-sized pyramids, which cannot be realized by a direct method using **BP_{Chol}**.

Introduction

Supramolecular polymerization is a key molecular self-assembly process induced by directional noncovalent interactions like hydrogen bonds in nonpolar solvents, leading to well-defined nano- and mesoscopic architectures like one-dimensional (1D) fibrous nanostructures, categorized as supramolecular polymers (SPs).^{[1] [2] [3] [4] [5]} Stimuli responsiveness can be introduced due to the noncovalently assembled systems.^{[6] [7] [8] [9]} Especially, functional SPs with highly ordered internal π -stacked structures of π -conjugated molecules have attracted attention not only for the changes in optical properties due to their basic aggregation,^{[10] [11] [12] [13] [14] [15]} but also for the unique physical properties, such as 1D long-range exciton transfer^{[16] [17] [18]} and charge carrier mobility.^{[19] [20]} In general, supramolecular polymerization into sophisticated nanostructures, such as nanotubes^[21], nanosheets^{[22] [23]}, and nanohelix^{[24] [25]}, requires a hierarchical self-assembly process from molecularly dispersed states (monomers) under thermodynamic control like slow-cooling a hot monomer solution (Figure 1a).^[26] To obtain discrete SPs with hydrophobic surfaces as a homogeneous colloid

solution, supramolecular polymerization in the nonpolar media is essential. However, π -extended compounds with hydrogen-bonding moieties show low solubility in common nonpolar solvents, preventing the establishment of suitable conditions for supramolecular polymerization. The solubility of hydrogen-bonding π -conjugated molecules has been enhanced by the introduction of multiple alkyl chains for perylene bisimide^{[27] [28] [29]}, porphyrin^{[30] [22] [31]}, and the other π -skeletons^{[32] [33] [34] [35]}. However, increasing the number of hydrogen bonding sites and further π -extension limits the applicability of the strategy. As an alternative strategy for solubility enhancement, the use of thermal or photo-precursors corresponding to target π -skeletons such as tetrabenzoporphyrin (BP) and pentacene is effective. Owing to the higher solubility of precursors, the solution-processable fabrication of organic thin-film electronic devices, such as organic field-effect transistors^{[36] [37] [38] [39]} and photovoltaic devices^{[40] [41]}, has been achieved via in-situ conversion from precursors to target pristine compounds in the solid state, called precursor approach.^{[41] [42]} The introduction of the precursor approach into supramolecular polymerization systems can provide a stimuli-induced one but is still rare^[43], and a strategic example using the thermal precursor approach has not been reported. Furthermore, the indirect method using soluble precursors enables the extension of supramolecular assemblies at high concentrations, which cannot be achieved in the direct method (Figure 1b).

BP is a π -extended porphyrin with four benzene-rings fused at the respective β -pyrrolic positions and exhibits high ultraviolet-visible (UV-vis) absorption ability as a dye molecule (molar coefficient (ϵ) > 10^5 M⁻¹ cm⁻¹)^{[44] [45]}, superior charge carrier mobility in the crystalline state as p-type organic semiconductors^{[46] [47]}, and conductivity of BP aggregates in ionic states^[48]. The inherently low solubility of BP, derived from the strong aggregation tendency, is expected to decrease further by introducing hydrogen bonding moieties, which are essential for supramolecular polymerization. The SP formation of BP derivatives is still challenging, and therefore the in-depth supramolecular nanostructure and chiroptical properties are veiled.

Herein, we report a novel thermal-induced supramolecular polymerization of a hydrogen-bonding BP derivative with cholesterol side groups (**BP_{Chol}**, Figure 1c) into chiral aggregates via the corresponding soluble thermal precursors as inactive monomers. This polymerization under the indirect method is driven in the high-boiling-point and nonpolar solvent, 1,2,3,4-tetrahydronaphthalene (tetralin), through two steps: the thermal conversion of a precursor of **BP_{Chol}**, tetracyclo[2.2.2]octadiene(BCOD)-fused porphyrin derivative

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(**CP**_{Chol}, Figure 1c) via the retro-Diels–Alder reaction in the hot solution and the subsequent self-assembly of converted **BP**_{Chol} upon cooling (Figure 1b). By monitoring the UV-vis absorption spectra in tetralin, we confirmed the thermal conversion of **CP**_{Chol} to **BP**_{Chol} and the cooperative supramolecular polymerization of **BP**_{Chol} into J-type aggregates with a slipped stacking mode. High-resolution microscopic analysis revealed the formation of unique pyramidal multilayer structures with a spiral nature. The circular dichroism (CD) spectra exhibited a left-hand-biased supramolecular chirality induced by twisted stacks reflected from cholesterol chirality. To the best of our knowledge, this is the first

observation of CD signals arising from chirally stacked BPs. Notably, the supramolecular polymerization process was affected by the cooling rate of hot solutions. Fast cooling led to stable small nanosheet aggregates with long-term stability, while natural cooling produced larger pyramidal structures. By using the nanosheets as a “seed”, the seed-induced supramolecular polymerization was achieved. Finally, we demonstrated a supramolecular polymerization at high concentration (mM level) into micro-sized pyramids by the indirect method using **CP**_{Chol}, which could not be realized by a direct method using **BP**_{Chol} due to the limitation of solubility.

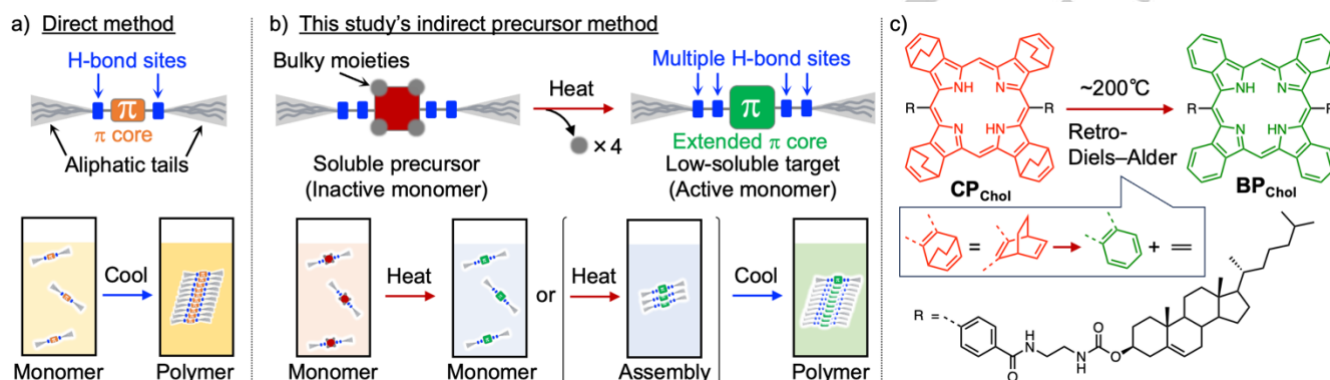


Figure 1. (a) General direct and (b) this study's indirect methods for supramolecular polymerization. (c) Molecular structures of **CP**_{Chol} and the thermally converted **BP**_{Chol} via the retro-Diels–Alder reaction.

Results and Discussion

Molecular design and solid-state thermal conversion. A supramolecular monomer with the BP core unit for π - π stacking was designed, incorporating amide and carbamate groups for hydrogen bonding and cholesterol groups for chiral SP formation on both arms of the BP (**BP**_{Chol}, Figure 1c). The cholesterol groups were also expected to stabilize SPs in nonpolar solvents. As the precursor, **CP**_{Chol} was synthesized according to Scheme S1. **CP**_{Chol} and intermediates were characterized by ¹H and ¹³C nuclear magnetic resonance (NMR) spectroscopies and high-resolution mass spectrometry (HRMS) (Figures S1–S6). To investigate a solid-state thermal conversion from **CP**_{Chol} to **BP**_{Chol}, we conducted the thermogravimetric analysis using **CP**_{Chol} powders under argon flow. A weight loss by ca. 6% between 130 and 250 °C was confirmed (Figure S7), which is nearly consistent with the theoretical weight difference with releasing four ethylene gas molecules per one **CP**_{Chol} molecule (−6.3%) via the retro-Diels–Alder reaction. This result indicates the conversion to **BP**_{Chol} in the temperature range. Pure **BP**_{Chol} powders were obtained by heating **CP**_{Chol} powders under reduced pressure at 200 °C using a Kugel-Rohr for 60 min. The color change of powders from deep red of **CP**_{Chol} to deep green of **BP**_{Chol} was confirmed (Figure 2a). The characterization of **BP**_{Chol} was performed by NMR and HRMS analyses (Figures S8–S10).

To obtain insights into hydrogen-bonding interactions in the aggregates state, infrared (IR) spectra of **CP**_{Chol} and **BP**_{Chol} powders were measured using the attenuated total-reflection (ATR) method. The assignment was performed based on the normal-mode analysis using the density functional theory (DFT) calculation (Figure S11 and Tables S1, S2). IR band was

observed at ca. 3350 cm^{−1} for **CP**_{Chol} and ca. 3280 cm^{−1} for **BP**_{Chol} (Figure 2b), assignable to the N–H stretching vibration (ν (NH)) mode at the amide and carbamate moieties. These bands are shifted to the lower wavenumber region compared to the free ν (NH) band reported previously (3425 cm^{−1})^[49], suggesting the formation of hydrogen bonds. The larger shift of **BP**_{Chol} indicates stronger hydrogen bonds. Additionally, IR bands assignable to the C=O stretching vibration (ν (CO)_c) mode at carbamate moieties were observed at 1728 and 1720 cm^{−1} for **CP**_{Chol}, and 1716 and 1698 cm^{−1} for **BP**_{Chol} (Figure 2b). The lower wavenumber bands of **BP**_{Chol} indicate stronger hydrogen bonds between carbamate moieties of **BP**_{Chol}. In contrast, IR bands (ν (CO)_a) at amide moieties were observed at 1624 cm^{−1} for **CP**_{Chol}, and 1635 cm^{−1} for **BP**_{Chol}, indicating weaker hydrogen bonds between amide moieties of **BP**_{Chol}. These results suggest that hydrogen bonding orders at carbamate and amide moieties can be changed synchronously via the conversion of bulky BCOD moieties to flat benzo moieties.

UV-vis absorption spectra of **CP**_{Chol} and **BP**_{Chol} in THF as monomeric states were measured using each diluted solution (*c* = 1.0 μ M). **CP**_{Chol} solution exhibited absorption bands at 502 and 574 nm and a relatively intense broad absorption band at 403 nm, corresponding to the Q and Soret bands of porphyrin units, respectively (Figure 2c). For **BP**_{Chol}, redshifted Q bands at 610 and 667 nm were detected with two sharp and redshifted Soret bands at 422 and 436 nm. Their bands are assigned using excited-state calculations, as shown in Supporting information (Figure S12 and Tables S3, S4). The split bands in the Q and Soret regions correspond to electronic transitions with different transition dipole moments in the y- and x-directions at BP units, respectively. Additionally, the photoluminescence (PL) spectrum under excitation at 612 nm exhibited a sharp PL peak at 668.5

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nm, and the PL excitation spectrum was consistent with the absorption spectrum (Figure 2d). The Stokes shift is small (34 cm^{-1}), indicating that structural changes of the BP unit in the excited state are subtle due to the rigid π -unit.

The solubility of **CP**_{Chol} and **BP**_{Chol} in THF and CHCl_3 was compared using UV-vis absorption spectra (Figure S13). As expected, **CP**_{Chol} showed higher saturated concentrations than those of **BP**_{Chol} ($[\text{CP}_{\text{Chol}}]_{\text{sat}} = 190\text{ }\mu\text{M}$ (THF) and $1100\text{ }\mu\text{M}$ (CHCl_3), $[\text{BP}_{\text{Chol}}]_{\text{sat}} = 52\text{ }\mu\text{M}$ (THF) and $9\text{ }\mu\text{M}$ (CHCl_3). The higher solubility of **CP**_{Chol} was attributed to the presence of bulky BCOD moieties.

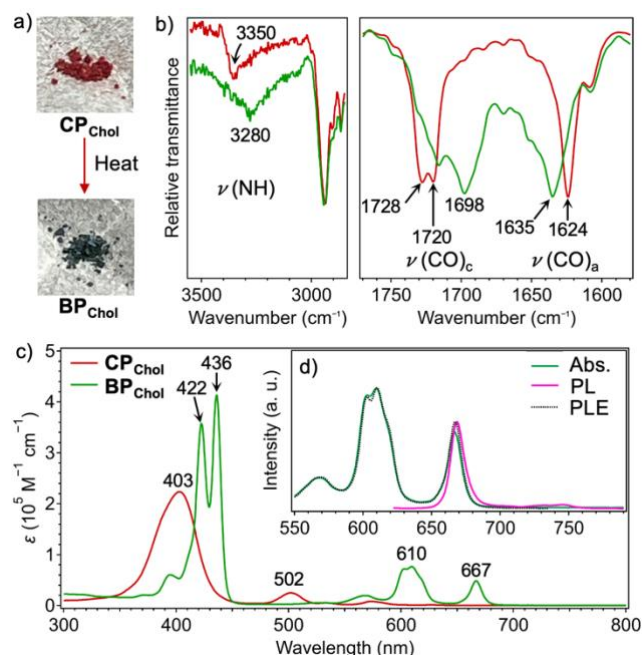


Figure 2. (a) Photographs of **CP**_{Chol} powders and thermally converted **BP**_{Chol} powders. (b) IR spectra of **CP**_{Chol} (red) and **BP**_{Chol} powders (green). (c) UV-vis absorption spectra of **CP**_{Chol} and **BP**_{Chol} monomers in THF. (d) The PL ($\lambda_{\text{ex}} = 612\text{ nm}$) and PL excitation (PLE) spectra ($\lambda_{\text{em}} = 745\text{ nm}$) of **BP**_{Chol} monomers in THF. The absorption spectrum is shown for comparison.

Solution-state thermal conversion and subsequent supramolecular polymerization.

Next, we attempted a solution-state thermal conversion of **CP**_{Chol} to **BP**_{Chol} via the retro-Diels–Alder reaction. To achieve the thermal conversion and supramolecular polymerization, tetralin was selected because of the high boiling point at $207\text{ }^\circ\text{C}$ and the low polarity. A solution of **CP**_{Chol} ($c = 10\text{ }\mu\text{M}$) was prepared in a vial and stirred under heating on a $200\text{ }^\circ\text{C}$ hotplate (solution temperature: ca. $180\text{ }^\circ\text{C}$) in argon. The reaction progress was monitored by time-dependent absorption spectral changes in the Q band region

using a fiber-type spectroscopy (see Supporting Information). As shown in Figure 3a, the monomer spectrum of **CP**_{Chol} with a peak at 506 nm was confirmed at room temperature, and upon heating, the absorption band of **CP**_{Chol} decreased with increasing new bands at 575 , 611 , and 677 nm . These spectral changes reached saturation after 60 min (Figure 3b). The spectrum after heating is close to those of **BP**_{Chol} monomers in THF (Figure 2c), suggesting that the conversion of **CP**_{Chol} to **BP**_{Chol} was achieved in solution. Notably, we confirmed that natural cooling of the hot solution at room temperature resulted in a change in solution color from green-blue to green (Figure 3d). In the cooling process, an increase in redshifted new bands at 652 and 693 nm was observed with a decrease in the monomer bands (Figure 3c). This redshift indicates the formation of supramolecular aggregates with slipped stacks between BP units, namely J-type aggregates.^[10]

On the basis of the optimized condition, we investigated the chiroptical properties of the aggregates in detail. To confirm supramolecular chirality induced by aggregation, we measured CD spectra of **BP**_{Chol} aggregates in tetralin. They were prepared by the solution-state thermal conversion and subsequent cooling and aging at room temperature for 1 hour . The CD signals of the solution ($c = 10\text{ }\mu\text{M}$) were observed at 454 , 642 , and 684 nm as positive peaks, and at 390 , 493 , 659 , and 700 nm as negative peaks (Figure S14). Upon increasing the concentration to 30 , 50 , 70 , and $100\text{ }\mu\text{M}$, CD intensity increased with maintaining the shape (Figure 3e,f). Although the molar CD ($\Delta\epsilon$) values at 454 and 682 nm showed a slightly increasing trend upon increasing concentrations, the value at the lowest concentration ($10\text{ }\mu\text{M}$) is not largely different from that of the highest concentrated solution ($c = 100\text{ }\mu\text{M}$) (Figure 3h). This result suggests that **BP**_{Chol} forms well-biased chiral aggregates even in $10\text{ }\mu\text{M}$. Considering that the CD spectrum of **CP**_{Chol} ($c = 100\text{ }\mu\text{M}$) was silent before heating (Figure S14), the CD signals emerged by the conversion to **BP**_{Chol}. Furthermore, given that **BP**_{Chol} monomers in THF ($c = 30\text{ }\mu\text{M}$) were CD silent (Figure S14), the CD signals of **BP**_{Chol} aggregates in tetralin are due to the supramolecular chirality. The zero-crossing point of the bisignate CD signals (684 and 700 nm) was located at 692 nm , which is nearly consistent with the absorption maximum at the Q band (693 nm) (Figure 3f). This result indicates a chiral exciton coupling between electric transition moments of the BP units^[50–51]. The detection of negative CD signals at the longer wavelength in the bisignate signals means a predominant counterclockwise (CCW) twisted stack (Figure 3g). Additionally, the relationship between the bisignate CD signal and the local CCW twisted stack was also supported by theoretical simulations focused on the Q band region (Figure S15).^[52]

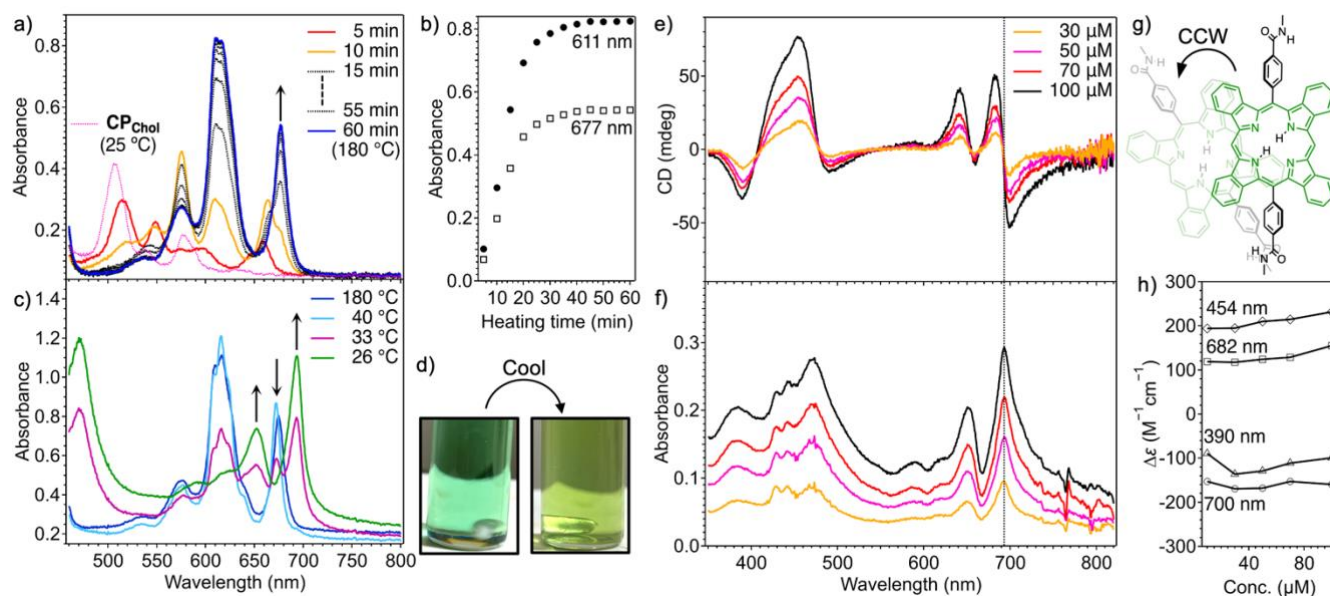


Figure 3. (a) Time changes in absorption spectra of **CP**_{chol} in tetralin ($c = 10 \mu\text{M}$) at ca. 180°C . The normalized absorption spectrum of **CP**_{chol} at ca. 25°C before heating is shown for comparison. (b) Plots of the absorbance as a function of heating time. (c) Temperature changes in absorption spectra of **BP**_{chol} in tetralin ($c = 10 \mu\text{M}$) during natural cooling of the hot solution, after heating for 120 min, at room temperature. (d) Photographs for the solution color change of **BP**_{chol} upon natural cooling. (e, f) CD and UV-vis absorption spectra of **BP**_{chol} in tetralin at different concentrations. (g) Schematic illustration of the dimer structure with CCW twisted stacks. (h) Plots of the $\Delta\epsilon$ as a function of concentration.

Supramolecular pyramid structures. We evaluated the supramolecular structures of resulting chiral **BP**_{chol} aggregates by transmission electron microscopy (TEM) observation of samples prepared by spin-coating the solution. The TEM images for $c = 10 \mu\text{M}$ reveal the formation of pyramid-like multilayer structures with a spiral nature at the center (Figure 4a,b and S16a–c). At the higher concentration ($100 \mu\text{M}$), the TEM images display larger pyramidal multilayers as extended structures (Figures 4c,d, and S16d–h). Atomic force microscopy (AFM) images also supported the pyramid structures (Figure 4e) and the spiral nature (Figure S17c,d). The cross-sectional analysis revealed a height difference between layers of ca. 5.5 nm (Figure S17a,b). Also, cracks in the pyramid were observed by AFM and TEM images (Figures 4e, S16b,h, S17a,b), indicating it deforms under the drying process on a substrate.

Furthermore, out-of-plane X-ray diffraction (XRD) of the film sample, prepared by drop-casting the solution, showed a diffraction peak at $2\theta = 1.7^\circ$ corresponding to a layer spacing of 5.2 nm in the vertical direction to the substrate surface (Figure S18a). The IR spectrum of the same sample exhibited the $\nu(\text{NH})$ band at 3292 cm^{-1} , which is smaller than the reported value (3313 cm^{-1})^[49] of hydrogen-bonded bands of the cholesterol

derivative with the same hydrogen-bonding moieties as **BP**_{chol}, suggesting the formation of stronger hydrogen bonds (Figure S18b). Considering that the long-axis length of a geometry-optimized structure of **BP**_{chol} estimated by DFT calculations is $5\text{--}6 \text{ nm}$ (Figure S19a, Table S5), each monolayer component is formed by two-dimensional like aggregation of **BP**_{chol} with edge-on orientation to the sheet surface (Figure 4f). The formation of rare pyramidal multilayers but not flat monolayers suggests that supramolecular polymerization occurs via the growth of a spiral-shaped nucleus (Figure 4f). As the in-depth packing structure cannot be analyzed by single-crystal (SC) XRD, we propose a possible aggregation model using the SC-XRD structure of an amide-group-functionalized BP derivative with the same part structure as **BP**_{chol}. The BP derivative undergoes twist J-type stacking and extended zigzag stacking via intermolecular hydrogen bonds between amide groups (Figure S20a).^[53] In addition, the absorption band of the J-aggregates at 690 nm is nearly consistent with that of **BP**_{chol} at 693 nm , supporting the J-aggregation of **BP**_{chol}. Assuming that a similar hydrogen-bonding pattern forms in the self-assembly of **BP**_{chol}, it can form twisted zigzag oligomers but not linear ones (Figure S20b).

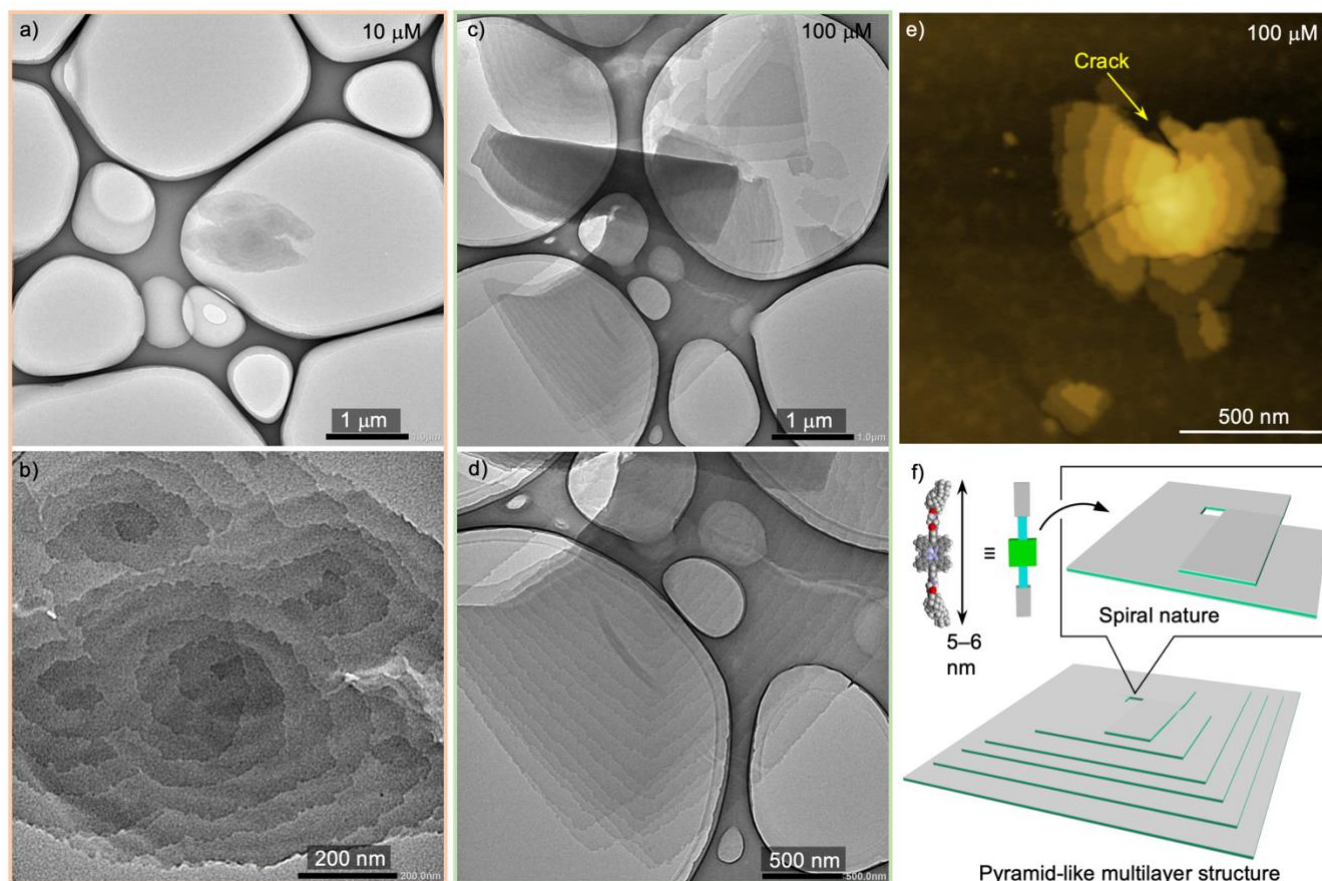


Figure 4. (a, b) TEM images of BP_{chole} aggregates prepared from the aggregate solution ($c = 10 \mu\text{M}$). (c, d) TEM and (e) AFM images of BP_{chole} aggregates prepared from the aggregate solution ($c = 100 \mu\text{M}$). These aggregates were aged for 60 min at room temperature after thermal conversion. (f) Schematic illustration of an expected assembly structure.

Cooperative self-assembly mechanism. To obtain insight into an aggregation mechanism of BP_{chole} , we evaluated the disassembly process by temperature-dependent UV-vis absorption spectra of the obtained aggregates in tetralin ($c = 30, 50, 70, 100 \mu\text{M}$). Their aggregate solutions were measured after thermal conversion and subsequent aging for 60 min at room temperature. Upon heating the solution of $c = 100 \mu\text{M}$, gradual spectral change with a decrease of the aggregate bands at 384, 473, 652, and 694 nm and an increase of the monomer bands at 428, and 441 nm was observed from ca. 340 K (Figures 5a, S21a). However, most of the aggregate bands were maintained at 373 K, and complete disassembly to monomers was not achieved even at lower concentrations ($c = 30, 50, 70 \mu\text{M}$) (Figure S21b–e). Therefore, we investigated a much lower concentration solution of $c = 5 \mu\text{M}$. Notably, BP_{chole} existed as monomers during aging for 60 min at room temperature, as confirmed by the detection of sharp monomer bands (Figure 5c). Afterward, further aging allowed gradual spectral changes attributed to self-assembly (Figure 5c). The plots of ϵ at 441 and 691 nm as a function of aging time follow a sigmoid curve (Figure 5d). The presence of the lag time and the sigmoidal transition indicate that BP_{chole} undergoes a nucleation–elongation (cooperative) self-assembly mechanism.^[54] The presence of lag

time can be explained by intramolecular hydrogen bonds (Figure 5b).^[29] The molecular structure closed by hydrogen bonds is represented by geometry optimization (Figure S19b and Table S6). It acts as a dormant monomer, which can be a supersaturated solution. After sufficient aging for 72 hours, we heated the aggregate solution and successfully detected a complete disassembly into monomers (Figure 5e). The temperature-dependent change in ϵ at 695 nm was normalized to be treated as the degree of aggregation (α) as a function of temperature (Figure 5f). This heating curve shows a non-sigmoidal transition rather than a sigmoidal one, which is fitted by the cooperative model proposed by Meijer and co-workers,^[24] as shown in Supporting Information. The fitting analysis provided the elongation temperature ($T_e = 365 \text{ K}$), and the enthalpy change during elongation ($\Delta H_e = -86 \text{ kJ mol}^{-1}$). In addition, the dimensionless equilibrium constant at T_e ($K_a = 7.5 \times 10^{-5}$) was sufficiently low compared to 1. This result suggests that the self-assembly of BP_{chole} occurs with a large gap between nucleation and elongation constants, namely a high degree of cooperativity. Additionally, the thermal reversibility of BP_{chole} chiral aggregates ($c = 10 \mu\text{M}$) was confirmed by CD spectra and TEM images before and after heating at 200 °C and cooling to room temperature (Figure S22).

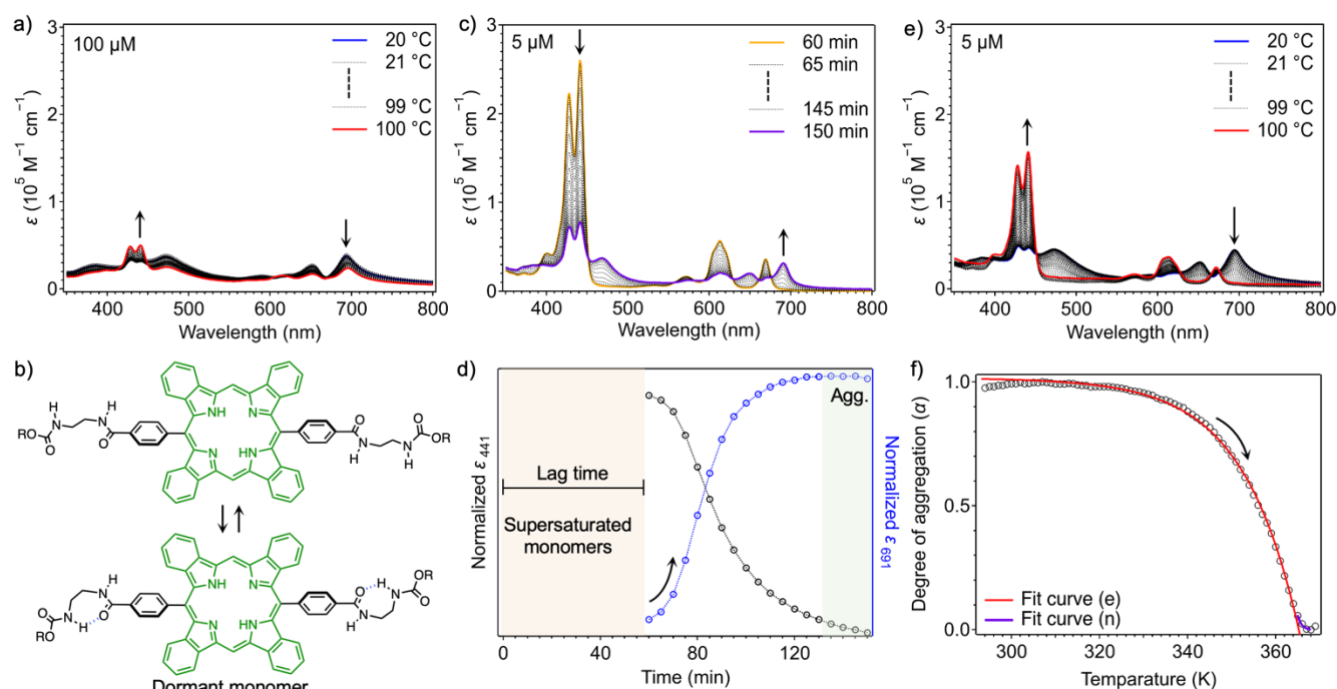


Figure 5. (a) Temperature-dependent UV-vis absorption spectra of BP_{choi} in tetralin ($c = 100 \mu\text{M}$). (b) Intramolecular hydrogen bonding of BP_{choi}. (c) Time-dependent absorption spectra of BP_{choi} in tetralin ($c = 5 \mu\text{M}$) and (e) temperature-dependent absorption spectra. (d) Plots of the molar coefficient (ϵ) at 441 nm (black) and 691 nm (blue) as a function of aging time. (f) Degree of aggregation (α) of BP_{choi} in tetralin as a function of temperature. The α value was calculated from the absorbance values at 695 nm. The fit curves (e) and (n) correspond to fitting curves with the theoretical cooperative model in the elongation and nucleation processes, respectively.

Stable nanosheets formed under kinetic control and seed-induced polymerization.

As the self-assembly pathway of BP_{choi} in tetralin can be affected by the kinetic effect, we conducted a faster cooling of a hot solution at ca. 180 °C by immersing the vial in ice water, compared to the natural cooling method mentioned before. Each aggregate ($c = 10$ and $100 \mu\text{M}$) obtained by the fast cooling and subsequent aging at room temperature for 0 and 30 min exhibited slightly sharp CD signals compared to those obtained by natural cooling and aging at room temperature for 60 min (Figure S23a). The CD spectral shape was maintained, indicating that the predominate CCW twist stacking is not affected by cooling rates. The TEM observation for $10 \mu\text{M}$ revealed the formation of smaller monolayer-like nanosheets with ca. 200 nm in width as major aggregates (Figures S23b–f), different from the case of naturally cooled multilayer aggregates with 500–1500 nm in width (Figures 4a,b, S16a–c). This result indicates that the CD signals are not affected by morphological difference between monolayers and multilayers. A similar trend was confirmed for $100 \mu\text{M}$ (Figures 4c,d, 6b, S16d–h, S24a–c). The morphological difference in cooling rates is probably due to each different frequency of nucleation (Figure 6d). In the case of the fast-cooling pathway, the nucleus is rapidly formed in relatively large quantities, in which the number of monomers essential for elongation of the nucleus decreases compared to the case of the slower natural-cooling pathway. Hence, the fast cooling provides a larger number of small sheet aggregates. Notably, we found that the dispersed sheets at $c = 100 \mu\text{M}$ did not show agglomeration among sheets into larger aggregates even after aging for 9 days, maintaining the homogeneous solution (Figure 6c, S24d–f). No

apparent changes were observed in the CD spectrum after aging for 17 days (Figure 6a). These results demonstrate the high stability of the small sheets formed kinetically in tetralin. This is presumably due to the rough sheet surface composed of bulky cholesterol groups, which can suppress further agglomeration of nanosheets, and the strong aggregation ability of BP_{choi} that prevents structural transitions.

The stable nanosheet can act as a “seed” in cooperative supramolecular polymerization. Therefore, we investigated whether the monolayer nanosheet obtained from fast cooling could induce supramolecular polymerization. A seed solution ($c = 30 \mu\text{M}$) in tetralin was prepared by fast cooling, and a fraction of the solution was added to a supersaturated monomer solution ($c = 5 \mu\text{M}$) under stirring. The resulting molar ratio is $[\text{BP}_{\text{choi}}]_{\text{seed}} : [\text{BP}_{\text{choi}}]_{\text{mono}} = 1:50$. The effect of seed addition was investigated by monitoring absorbance at 691 nm, which corresponds to the aggregate band, as a function of time (Figure 6e). As expected, the addition of seed induced a sharp increase in absorbance while the supersaturated monomer solution showed a slower sigmoidal change. This result suggests the seed-induced supramolecular polymerization and supports the nucleation-elongation model.^{[30] [57]} Additionally, we confirmed the size extension of nanosheets from ca. 200 nm (seed) to >500 nm (aggregate) by TEM images (Figures 6f, S25). Notably, the monolayer sheet structures were maintained after the extension, also corroborating the seed-induced supramolecular polymerization.

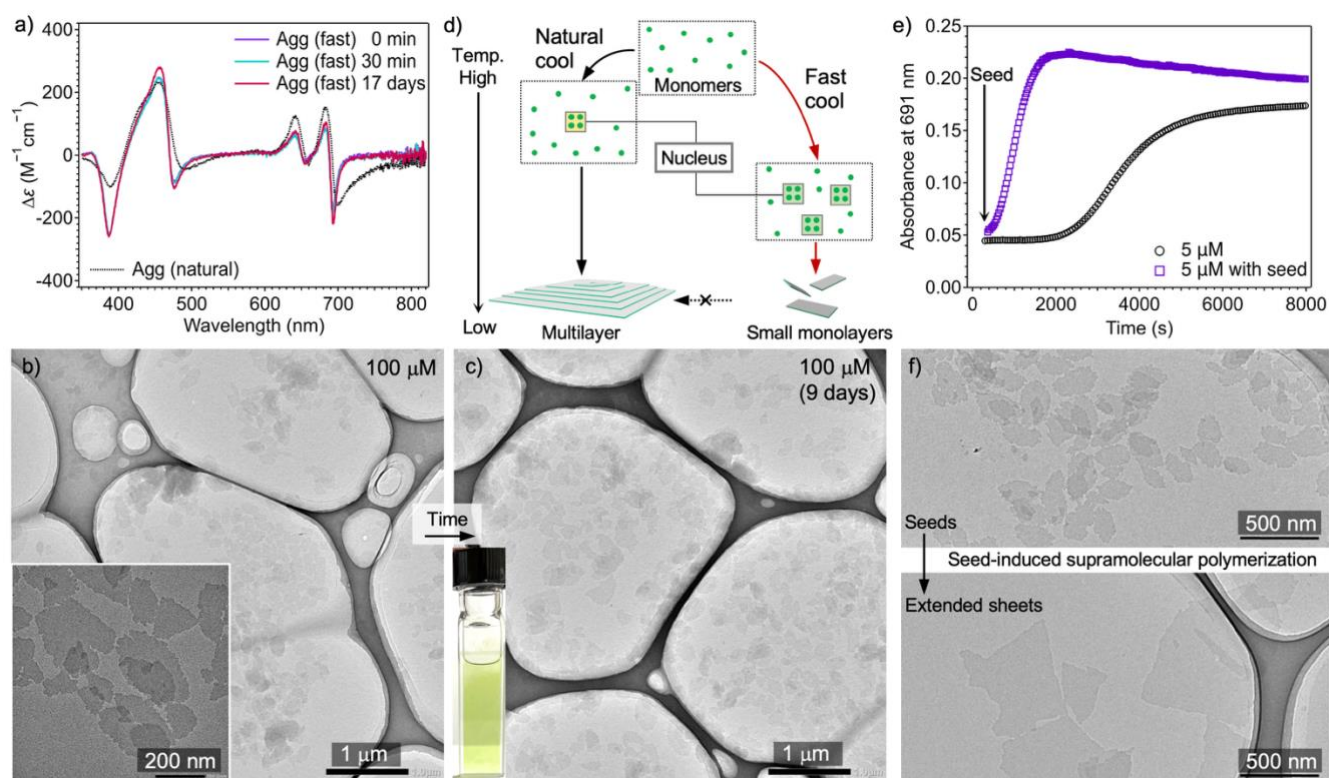


Figure 6. (a) CD spectra of fast-cooled BP_{chole} aggregates in tetralin at 100 μM , prepared by immersing the solution in ice water. The spectrum of naturally cooled aggregates is shown for comparison. (b) TEM image of the BP_{chole} aggregates at 100 μM formed by the fast cooling and aging for (b) 30 min and (c) 9 days, spin-coated from their aggregate solutions. The inset image in (b) is a magnified TEM image. The inset photograph in (c) is a homogeneous solution in a 1 mm quartz cell after aging for 9 days. (d) Cooling-rate dependent self-assembly pathway models of BP_{chole} aggregates. (e) Changes in absorbance at 691 nm as a function of time in the solution at 5 μM with and without seeds under stirring. (f) TEM images of seeds (30 μM) and the extended sheets.

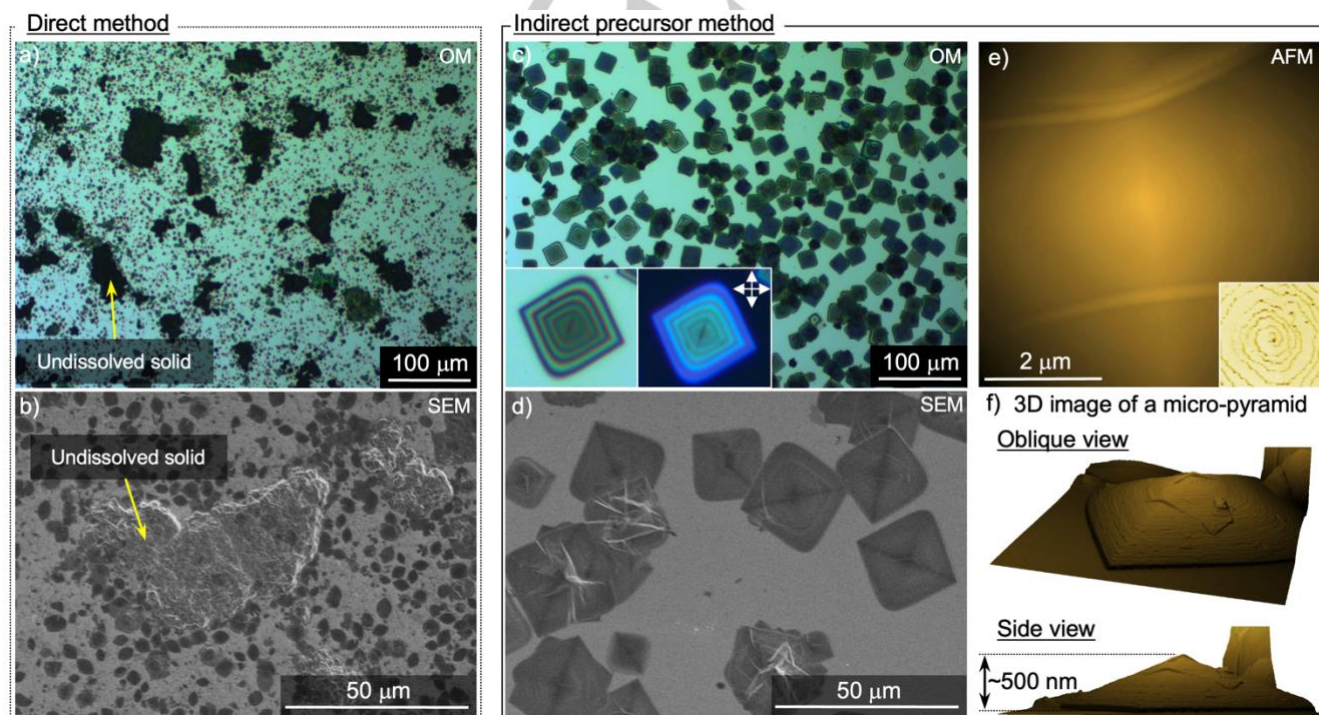


Figure 7. (a) Optical microscopic (OM) image and (b) SEM image of BP_{chole} aggregates ($c = 1.0 \text{ mM}$), prepared by the direct method. (c) OM image, (d) SEM image, (e) AFM height, and phase images of BP_{chole} aggregates ($c = 1.0 \text{ mM}$), prepared by indirect precursor method. Insets in (c) show the magnified OM and polarized optical microscopic (POM) images. (f) 3D images of a pyramidal structure of BP_{chole} generated from AFM images.

Comparing direct and indirect methods. Finally, we compared the indirect precursor method for supramolecular polymerization using **CP_{Chol}**, mentioned above, and a general heating-cooling (direct) method of **BP_{Chol}** (Figure S26a). For the concentration at 100 μM , **BP_{Chol}** aggregates were formed by the direct method, in which the almost same UV-vis absorption spectrum and TEM images as those by the indirect method were obtained (Figure S26b,c,e). This result supports that the solution-state retro-Diels–Alder reaction in the indirect precursor method occurs without forming any byproducts and Diels–Alder reaction to **CP_{Chol}**. However, the CD signals of aggregates by the direct method were weak compared to those by the indirect precursor method (Figure S26d). This difference is presumably due to the different nucleation processes at high temperatures. In the indirect method, the active **BP_{Chol}** is gradually supplied for several hours via the retro-Diels–Alder, that is, the concentration of **BP_{Chol}** increases slowly. In contrast, the direct method affords a rapid increase in **BP_{Chol}**, leading to a different nucleation process. These results indicate that each method provides different aggregation pathways.

To demonstrate the superiority of the indirect method, we attempted a polymerization experiment at a higher concentration of 1.0 mM. In this high concentration, the solid of **BP_{Chol}** was not perfectly dissolved in tetralin even heating at 200 °C. Upon cooling, the dissolved **BP_{Chol}** self-assembled into multilayer structures with ca. 5 μm widths but ill-defined aggregates were also observed as a lump of undissolved **BP_{Chol}**, as confirmed by optical microscopy (OM), polarized optical microscopy (POM), scanning electron microscopy (SEM), and TEM (Figure 7a,b, S27). In sharp contrast, the indirect method enabled a perfect supramolecular polymerization without ill-defined aggregates of **BP_{Chol}** into larger rhombus-shaped crystalline structures with ca. 20 μm widths, as observed by OM and POM (Figure 7c, S28a,b). Notably, their images suggest a unique structure with an inherent periodic structure (Figure 7c inset). Additionally, SEM and TEM observation exhibited the multilayer structures with convex on top (Figures 7d, S28c–f). The AFM analysis revealed a pyramidal multilayer structure with a height of ca. 500 nm, with the average distance between monolayers estimated to be ca 5.5 nm (Figure 7f, S29). This monolayer thickness is consistent with that obtained at $c = 100 \mu\text{M}$ (Figure S17a,b), suggesting the fundamental assembly structure was not affected by concentrations. Accordingly, the cooperative supramolecular polymerization at high concentrations allowed a size extension of supramolecular pyramids to micro-levels.

Conclusion

In conclusion, we demonstrated a novel strategy for thermal-induced supramolecular polymerization of the poorly soluble π -extended tetrabenzoporphyrin derivative (**BP_{Chol}**) with hydrogen-bonding and chiral cholesterol moieties, triggered by the solution-state retro-Diels–Alder reaction of the corresponding precursor (**CP_{Chol}**). The supramolecular polymerization of BP derivatives is realized for the first time by using the thermal precursor approach. The thermal conversion of **CP_{Chol}** (inactive

monomer) to **BP_{Chol}** (active monomer) in tetralin was confirmed by monitoring the changes in UV-vis absorption spectra at high temperatures. The subsequent cooling led to the self-assembly of **BP_{Chol}** into pyramidal multilayer structures with a spiral nature, as revealed by CD spectra and high-resolution microscopic images. Notably, we uncovered the cooperative self-assembly mechanism based on analyzing time- and temperature-dependent absorption changes. Additionally, the cooling rate affected the self-assembly process, where fast cooling of the hot solution led to a different pathway, resulting in small monolayer nanosheets with long-term stability. By adding the nanosheets as seeds into a supersaturated monomer solution, the seed-induced supramolecular polymerization was achieved. Finally, we succeeded in the creation of crystalline micro-sized pyramids at a higher concentration using the indirect precursor method using **CP_{Chol}**, which is never led by a direct method from **BP_{Chol}**. The present strategy can facilitate the creation of undeveloped supramolecular polymers with semiconductor properties and the size extension to micro-levels because the indirect precursor method enables the supramolecular polymerization of insoluble π -extended molecules, leading to the development of supramolecular electronic devices.

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Keywords: tetrabenzoporphyrin • supramolecular chirality • self-assembly • precursor approach • pyramid structure

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