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Hierarchical Self-Assembly of a Bow-Shaped Molecule Bearing Self-Complementary Hydrogen Bonding Sites into Extended Supramolecular Assemblies

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Abstract: The bow-shaped molecule **1** bearing a self-complementary DAAD–ADDA (D = donor A = acceptor) hydrogen-bonding array generates, in hydrocarbon solvents, highly ordered supramolecular sheet aggregates that subsequently give rise to gels by formation of an entangled network. The process of hierarchical self-assembly of compound **1** was investigated by the concentration and temperature dependence of UV-visible and ^{1}H NMR spectra, fluorescence spectra, and electron microscopy data. The temperature dependence of the UV-visible spectra indicates a highly cooperative process for the self-assembly of compound **1** in decaline. The electron micrograph of the decaline solution of compound **1** (1.0 mM) revealed supramolecular sheet aggregates forming an entangled network. The selected area electronic diffraction patterns of the supramolecular sheet aggregates were typical for single crystals, indicative of a highly ordered assembly. The results exemplify the generation, by hierarchical self-assembly, of highly organized supramolecular materials presenting novel collective properties at each level of organization.

Keywords: hydrogen bonds · molecular recognition · self-assembly · supramolecular chemistry · supramolecular polymers

Introduction

Hierarchical self-assembly of molecules in a supramolecular network represents a versatile approach for developing well-defined polymolecular architectures with preprogrammed arrangements and tailored properties. Particular attention has been paid to supramolecular polymers, materials derived from the polyassociation of monomeric components through noncovalent interactions, that may have liquid-crystal features.[1–9] Hydrogen-bonded supramolecular polymeric chains were realized first through complementary, triple hydrogen-bonding ADA–DAD arrays (D: hydrogen-bonding donor; A: hydrogen-bonding acceptor) and gave rise to supramolecular liquid crystals.[5a]

For the structural features of liquid crystalline mesophases, the shape of individual molecules is crucial. In particular, rigid molecules of bent shape ("banana-shaped" compounds[10]) may form liquid crystals with a unique alignment that confers potential application for ferro- or antiferroelectric switching. Similarly, the shape of the monomeric molecules determines the morphology and ordering of supramolecular polymeric associations. The self-assembly of a number of such supramolecular polymers from linear-, disk-, macrocyclic-, and helical-shaped molecules has been described.[8,9] The self-assembly of rigid bent-shaped molecules could yield supramolecular polymers with interesting electronic and optical material properties as well as unique structural features.

Because of its versatility and directionality, hydrogen bonding is a suitable noncovalent interaction for generating supramolecular polymers. Since the degree of polymerization is strongly dependent on the strength of association, the number and the pattern of hydrogen bonds are important

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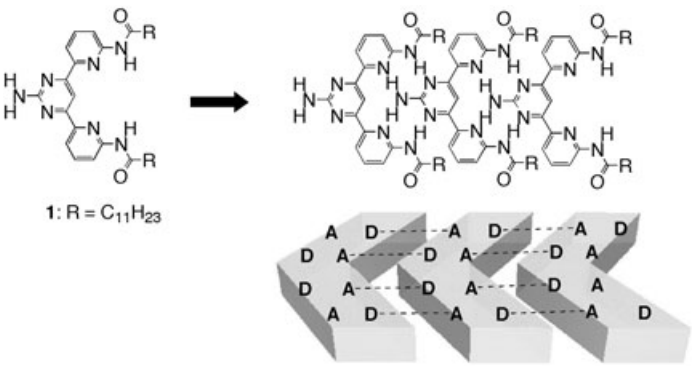
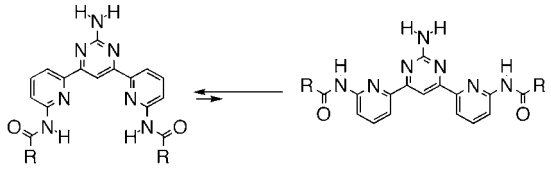
factors to obtain high degrees of polymerization. As indicated above, the first example of linear hydrogen-bonded supramolecular polymers were derived from complementary triple hydrogen-bonding ADA–DAD arrays.[5a] Strong complementary quadruple hydrogen bonding DDAA–AADD or DADA–ADAD arrays have extensively studied and the resulting supramolecular polymers have very concentration- and temperature-dependent viscosity.[9] Sextuple hydrogen bonding has been implemented between two-faced symmetrical heterocomplementary components, with DAD/DAD and ADA/ADA patterns.[6] As most of these studies have concerned the polyassociation of symmetrical monomers bearing complementary hydrogen-bonding sites (such as ADA-(spacer)-ADA + DAD-(spacer)-DAD or DDAA-(spacer)-AADD), the supramolecular polymers formed were also symmetric and possessed no directionality. In contrast, a supramolecular polymer derived from a monomer bearing two different self-complementary hydrogen-bonding faces will induce directional assembly, because of their nonsymmetric polyassociation. In biology, it bears analogy to the integrated network formed by the supramolecular polymer filament of actin, responsible for the mechanical integrity of the cell and critically involved in such processes as cell division, mobility, and plasticity.[11]

We thus envisioned that the self-assembly of bow-shaped molecules bearing self-complementary hydrogen-bonding patterns would allow the generation of a highly organized, directional supramolecular architecture. To this end, compound **1** was designed. It has a rigid bent-shape and self-complementary quadruple hydrogen-bonding DAAD–ADDA arrays and thus is expected to undergo polar supramolecular self-assembly as shown in Scheme 1. The structural codon represented by the pyridine–pyrimidine moiety is known to enforce a highly preferred *transoid* conformation around α,α′-interheterocyclic bonds,[12] thus conferring the orientation required for establishing the self-complementary array of hydrogen bonds to the heterocyclic subunits in **1** (Scheme 2).



Scheme 1. Structure of the monomer **1** bearing self-complementary DAAD–ADDA patterns of hydrogen bonding sites and its directional self-assembly into a ribbon-like supramolecular polymer through an array of four hydrogen bonds.



Scheme 2. Preferred conformation of compound **1**.

Herein, we report that compound **1** indeed forms highly ordered supramolecular sheet aggregates in hydrocarbon solvents in a cooperative manner and subsequently gives rise to gels with an entangled network of these supramolecular sheet aggregates.

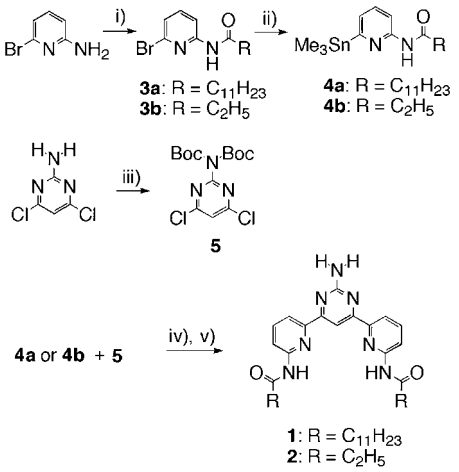
Abstract in French: *La molécule **1** présente une forme courbe en arc et porte un ensemble autocomplémentaire DAAD–ADDA de liaisons hydrogène. En solution hydrocarbonée, elle génère des feuillets supramoléculaires hautement ordonnés qui ensuite produisent des gels par formation d'un réseau enchevêtré. Le processus d'autoassemblage hiérarchisé du composé **1** a été étudié par l'examen des modifications des spectres UV-visible, de RMN et de fluorescence en fonction de la concentration et de la température, ainsi que par microscopie électronique. La variation des spectres UV-visible en fonction de la température indique que l'autoassemblage de **1** dans la décaline est un processus hautement coopératif. La micrographie électronique du sol formé par **1** dans la décaline (1.0 mM) révèle la formation d'agrégats supramoléculaires en feuillets constituant un réseau enchevêtré. La diffraction électronique de ces agrégats fournit des images typiques de cristaux, indiquant que l'ensemble est hautement ordonné. Les résultats obtenus illustrent la genèse, par autoassemblage hiérarchisé, de matériaux supramoléculaires hautement organisés présentant de nouvelles propriétés collectives à chaque niveau d'organisation.*

Results and Discussion

Synthesis of compounds 1 and 2: Compound **1** was synthesized according to Scheme 3. Treatment of 2-amino-6-bromo pyridine with dodecanoic acid chloride gave the amide **3a**, which was converted into the stannyl derivative **4a** by reaction with hexamethylditin in the presence of a $[Pd(PPh_3)_4]$ catalyst. Double coupling of 2.1 equivalents of **4a** with Boc-protected 2-amino-4,6-dichloropyrimidine (**5**) in the presence of $[Pd(PPh_3)_4]$ catalyst led to the Boc-protected compound **1** in 67% yield; subsequent deprotection by treatment with trifluoracetic acid (TFA) gave the desired compound **1** in 84% yield. Compound **2**, bearing shorter chains, was obtained following the same pathway.

Hierarchical and cooperative self-assembly of compound 1

^{1}H NMR spectroscopy in chloroform: The self-assembly of compound **1** was first investigated by evaluating the concen-



Scheme 3. i) RCOCl, Py, CH_2Cl_2, room temperature; ii) $Me_3SnSnMe_3$, 5 mol% $[Pd(PPh_3)_4]$, PhMe, 110 °C; iii) $(Boc)_2O$, DMAP, CH_2Cl_2, room temperature; iv) 5 mol% $[Pd(PPh_3)_4]$, DMF, 110 °C; v) TFA, CH_2Cl_2, room temperature.

tration dependence of ^{1}H NMR spectra in chloroform. At 1.0 mM, compound **1** showed a clearly resolved spectrum, corresponding to a molecular solution. On increasing the concentration of **1** up to 250 mM, significant and correlated down-field shifts were observed for both the amide-NH and the pyrimidine-NH_2 signals (Figure 1), indicating that self-

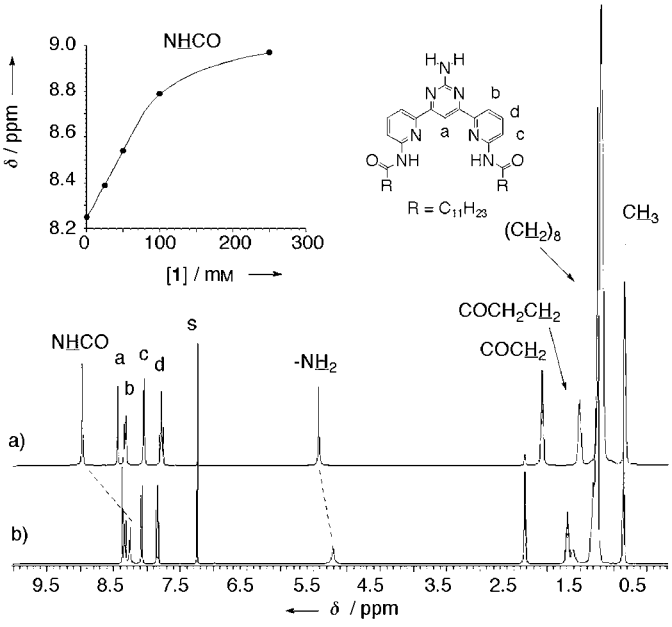


Figure 1. 400 MHz ^{1}H NMR spectra of **1** in $[D_1]CHCl_3$ a) 250.0 mM, b) 1.0 mM (s: solvent, inset: concentration dependence of chemical shift of the amide protons) at 25 °C.

assembly through hydrogen bonding was taking place and can be explained by the interaction mode depicted in Scheme 1. The plot of the chemical shift of the amide-NH signal against concentration was tentatively analyzed assuming a monomer–dimer equilibrium,[13] yielding a small association constant of 20 M^{-1}, which is coincident with the association constant between Boc-protected **1** and 2-aminopyrimidine (18 M^{-1}) (vide infra). In addition, all ^{1}H NMR signals remained sharp even at 250 mM, showing that higher order aggregations beyond the dimer were negligible in these conditions.

Remarkable up-field shifts were also observed for the signals of the alkyl chain protons, especially for the protons close to the amide groups (Figure 1). Such up-field shifts were not observed for the complexation between Boc-protected **1** and 2-aminopyrimidine (data not shown). Therefore, the observed up-field shifts do not result from the hydrogen bonding interaction, but from a shielding effect of the pyridine rings as shown in Figure 2. These results agree

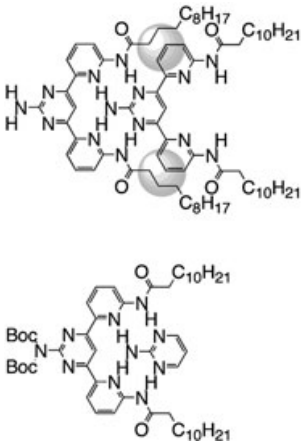


Figure 2. Schematic representation of the shielding effect due to the pyridine rings.

with the formation by compound **1** of well-defined self-assembled supramolecular assemblies through self-complementary quadruple hydrogen bonding as expected (Scheme 1).

*Gelation properties of compound **1***: The self-assembly of compound **1** in nonpolar solvents, in which hydrogen-bonding strength should be markedly enhanced, was then investigated by examining its gelation ability. The powder of compound **1** was dispersed in a given solvent (10.0 mM), the mixture was heated in a septum-capped test tube and then cooled to room temperature. Compound **1** was found to gelate hydrocarbon solvents such as decaline (mixture of *cis*- and *trans*-isomer), toluene, *p*-xylene, and paraffin. In contrast, compound **2** was not able to form a gel. The long alkyl chains play an important role in gel formation in the hydrocarbon solvents, presumably by preventing the crystallization of the compound. The gels of compound **1** were opaque not transparent, suggesting the presence of microscale aggregates. These aggregates displayed a birefringent character in the polarized optical micrograph of the decaline gel of compound **1**, indicating that they possessed a certain

extent of molecular ordering. The most stable gels were obtained with decaline as solvent; they were stable at room temperature for one month without precipitation. The gel formation was completely reversible with temperature. These results led us to evaluate the self-assembly properties of compound **1** in decaline in detail by spectroscopic and microscopic methods.

*UV-visible spectra of compound **1** in decaline*: The aggregation behavior of compound **1** was studied by using UV-visible spectroscopy, monitoring the changes in the $\pi\rightarrow\pi^*$ transitions. As shown in Figure 3, the UV-visible abbsorption

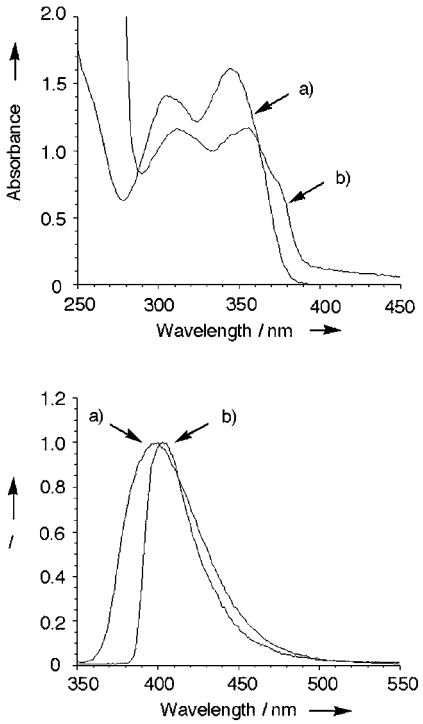


Figure 3. UV-visible spectra (top) and fluorescence spectra (bottom) ($\lambda_{ex}=340.0$ nm) of **1** (0.10 mM) in a) chloroform and b) decaline at 25 °C.

spectrum of compound **1** in decaline (0.10 mM) was different from that in chloroform. From the concentration dependence of the UV-visible spectra (data not shown) and the ^{1}H NMR spectrum (vide supra), it was confirmed that compound **1** was moleculary dissolved in this concentration range in chloroform. Red shifts (from 304.5 to 312.0 nm and from 345.0 to 355.0 nm) of the absorption bands in decaline with respect to those in chloroform were observed and a shoulder appeared around 378.0 nm. This result is consistent with an enhanced π-electronic conjugation of compound **1** resulting from an increased planarity due to the aggregation with hydrogen bonding and most probably to so-called J-type aggregation. Fluorescence spectra gave a red-shifted emission band around 403.0 nm in decaline relative to that in chloroform (400.0 nm).

To obtain further insight into the self-assembly of compound **1** in decaline, temperature-dependent UV-visible absorption spectroscopy measurements were performed. Raising the temperature of a solution of compound **1** (0.10 mM) in decaline from 25 °C to 65 °C resulted in blue shifts of the absorption bands, from 312.0 to 307.0 and 313.0 nm and from 355.0 to 343.0 nm, with a clear isosbestic point at 364.5 nm (Figure 4). At 65 °C, the spectrum had almost the

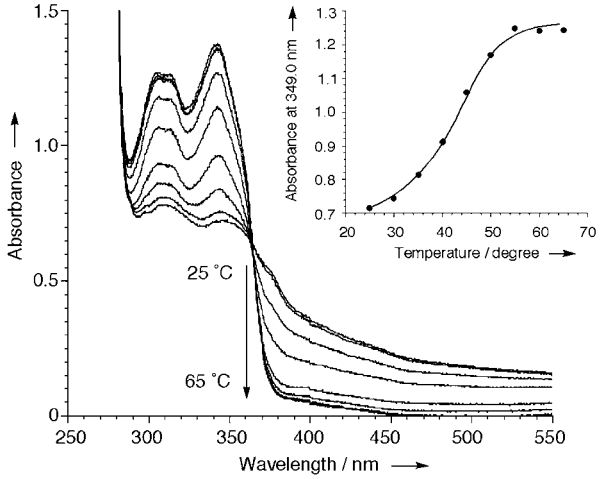


Figure 4. Temperature dependent UV-visible spectra of compound **1** (0.10 mM) in decaline (inset: absorbance at 349.0 nm at different temperatures).

same band shape as in chloroform at room temperature. Interestingly, it was found that a S-shaped transition took place around 45 °C (T_m), indicating that the formation of self-assembled aggregates by compound **1** in decaline was *cooperative*, that is, the self-assembled aggregates dissociate to the monomeric comound **1** in an all-or-nothing manner. The origin of a cooperative behavior may be attributed to the synergistic operation of hydrogen bonding and π–π stacking interactions in the self-assembly of compound **1**.

*Electron microscopy of the gel formed by compound **1***: To obtain insight into the microstructure of the gel formed by compound **1**, it was investigated by electron microscopy. Since a freeze–fracture image of compound **1** decaline gel could not be obtained, a direct observation of compound **1** in decaline (1.0 mM) was carried out.

The electron micrograph obtained revealed lamellar morphologies with an average width of 1.0 μm and thickness probably around 30 nm, since they are transparent to electrons (Figure 5). Very interestingly, the selected area electron diffraction pattern (inset of Figure 5) of the supramolecular sheet aggregates yields a clear high-resolution diffraction pattern, indicating a highly ordered self-assembly. The pattern indicates a unit cell with orthogonal projection. The cell parameters are $a=9.6$, $b=16.1$ Å (a axis is parallel to the length of the crystal).

Since molecular modeling calculations based on the supramolecular polymerization mode depicted in Scheme 1 suggested a width of about 20 Å for individual supramolecular

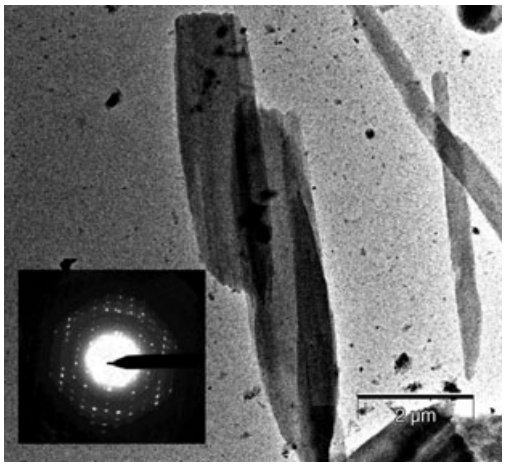


Figure 5. Electron micrograph of compound **1** in decaline (1.0 mM) obtained by the direct observation technique, (inset: selected area electron diffraction pattern).

sheets, the structures observed here could be ascribed as large bundles of the individual supramolecular sheets.

Presumably, the bow-shape and the self-complementary hydrogen bonding sites of compound **1** play an important role in the generation of such a highly ordered supramolecular sheet structure, as evidenced by electron diffraction (Figure 5). Molecular modeling calculations suggested that the self-assembly of compound **1** did not lead to a flat supramolecular sheet owing to steric hindrance between pyridine rings and alkyl chains (Figure 2). Nonetheless, supramolecular sheet aggregates were observed even in a chiral solvent (β-pinene; data not shown here); the most probable explanation is that compound **1** forms a zig-zag type self-assembly not a helical one, which would generally form fiber aggregates instead of sheet aggregates.

*Variable-temperature ^1H NMR spectra of compound **1** in decaline*: The ^{1}H NMR spectra of compound **1** (10 mM) in [D_{18}]decaline were measured in order to elucidate its self-assembly process (Figure 6). The signals were strongly broadened at room temperature (gel state) and underwent, when the sample was heated from room temperature to 100 °C, a significant sharpening due to the dissociation of the self-assembled aggregates. The gel collapsed above 80 °C; however, the sample was still turbid, indicating that self-assembled aggregates exist after the sol–gel transition. The sample became transparent above 90 °C, and the spectrum at 100 °C had almost the same peak shape as that of compound **1** (1.0 mM) in chloroform. Both amide-N*H* and pyrimidine-NH_2 proton NMR signals appeared around 60 °C and shifted first to lower-field (8.03 to 8.17 ppm: $\Delta\delta = 0.14$ ppm for amide-N*H* and 4.32 to 4.36 ppm: $\Delta\delta = 0.04$ ppm for pyrimidine-NH_2) up to 80 °C and then to higher-field (8.17 to 7.78 ppm: $\Delta\delta = -0.39$ ppm for amide-N*H* and 4.36 to 4.32 ppm: $\Delta\delta = -0.04$ ppm for pyrimidine-NH_2) from 80 °C to 100 °C. Hydrogen bonding in the gel at room temperture was confirmed by an FTIR measurement (hydrogen-bonded N–H stretching band 3230 cm^{-1} and C=O stretching bands 1663 and 1630 cm^{-1}). These spectral results, together with the microscopic image, suggest that compound **1** forms entangled and laminated self-assembled supramolecular sheets with hydrogen bonding and π–π stacking in the gel state at room temperature. On raising the temperature up to 80 °C, this network of self-assembled supramolecular sheets, which is responsible for the gel formation, would collapse to individual self-assembled supramolecular sheets as suggested by the change of macroscopic properties (from gel to opaque solution). This structural change would lead to downfield shifts of the amide-N*H* and pyrimidine-NH_2 signals by loss of the shielding effect due to π–π stacking. The upfield shifts, observed when the temperature is raised from 80 °C to 100 °C, correspond to breaking of the hydrogen bonds on dissociation of the self-assembled supramolecular sheets into monomeric compound **1** units.

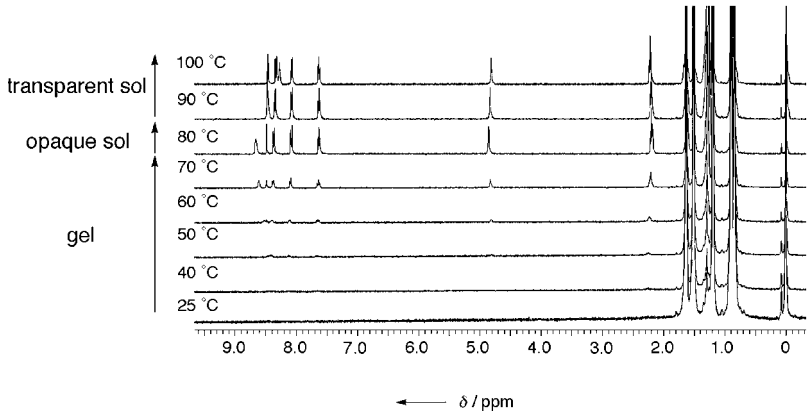


Figure 6. : Variable temperature 400 MHz ^{1}H NMR spectra of compound **1** (10.0 mM) in [D_{18}]decaline.

Conclusion

In conclusion, we have shown that compound **1** forms supramolecular sheet aggregates in hydrocabon solvents by directional assembly through a self-complementary, quadruple hydrogen-bonding DAAD–ADDA array (Scheme 1) and subsequently leads to supramolecular gels by formation of an entangled and laminated network of the supramolecular sheet aggregates. Most interestingly, the supramolecular sheet aggregates obtained were highly organized. This kind of dissymmetric, directional self-assembled structure with high molecular organization is of interest as model of biological self-assembly, such as that

found in actin filaments, as well as for the development of functional supramolecular entities, presenting novel emerging properties (such as optical,[14] magnetic,[15] ferroelectric, etc.) at each level of organization.

Experimental Section

General methods: All commercially available products were used without further purification. Flash column chromatography was performed on silica gel (40–63 μm, Merck). Melting points were recorded on a Büchi Melting Point B-540 apparatus and uncorrected. 400 MHz ^{1}H NMR spectra were recorded on a Bruker Avance 400 spectrometer. The solvent signal was used as an internal reference. UV-visible and fluorescence spectra were measured with Varian Cary 3 and Aminco-Bowman Series 2 spectrometers, respectively. FAB mass spectrometric measurements were performed by the Service de Spectrométrie de Masse, Institut de Chimie, Université Louis Pasteur.

Electron microscopy—direct observation: A 5 μL drop of a solution of the compound under investigation (1.0 mM) in decaline was deposited onto a 400 mesh EM grid covered with a carbon supporting film. To allow for sample adsorption, the excess solution was removed with a piece of filter paper (Whatman 2 or 5), and the grids were air dried. They were then placed in an Edwards Auto 306 Evaporator and rotary shadowed at an angle of 13° with platinum/tungsten. The grids were observed with a Philips CM12 electron microscope operating at 120 kV.

Synthetic procedures

***N*-(6-bromopyridin-2-yl)dodecylamide (3a)**: 2-Amino-6-bromopyridine (1.73 g, 10.0 mmol) and pyridine (2.10 mL, 26.0 mmol) were dissolved in dry dichloromethane (40 mL), and the solution was cooled to 5 °C in an ice bath. A solution of lauroyl chloride (2.84 g, 13.0 mmol) was added dropwise, and the reaction was allowed to proceed at room temperature for 15 hours. The reaction mixture was washed with water (2×50 mL) and a aturated aqueous solution of $NaHCO_3$, and the organic layer was dried over Na_2SO_4. The solvent was removed under vacuum. *n*-Hexane was added to the residual oil to afford compound **3a** as white solid. Yield: 3.29 g (93 %); m.p. 67.8–69.1 °C; ^{1}H NMR (400 MHz, $[D_1]CHCl_3$): $\delta = 8.16$ (d, $J = 8.4$ Hz, 1H), 7.80 (s, 1H), 7.53 (t, $J = 7.7$ Hz, 1H), 7.18 (d, $J = 7.6$ Hz, 1H), 2.34 (t, $J = 7.7$ Hz, 2H) 1.67 (m, 2H), 1.24 (m, 16H), 0.86 ppm (t, $J = 7.0$ Hz, 3H); FAB MS: *m/z* calcd for $[M+H]^+$: 355.1; found: 355.1

***N*-[6-(Trimethylstannanyl)pyridin-2-yl]dodecylamide (4a)**: Compound **3a** (1.00 g, 2.82 mmol), hexamethylditin (2.92 g, 1.5 equiv), and tetrakis(triphenylphosphino)palladium (161 mg, 0.141 mmol, 5 mol %) in degassed toluene (25 mL) were heated at 110 °C for 15 h. The reaction mixture was concentrated under vacuum. The resulting solid was dissolved in chloroform and subjected to chromatography (Al_2O_3, *n*-hexane/ethyl acetate = 20:1). Compound **4a** was obtained as a white solid. Yield: 850 mg (69 %); m.p. 58.9–59.9 °C; ^{1}H NMR (400 MHz, $[D_1]CHCl_3$): $\delta = 8.03$ (m, 1H), 7.85 (br s, 1H), 7.51 (m, 1H), 7.15 (m, 1H), 2.38 (m, 2H), 1.70 (m, 2H), 1.25 (m, 16H), 0.84 (m, 3H), 0.25 ppm (m, 9H); FAB MS: *m/z* calcd for $[M+H]^+$: 439.2; found: 441.2

2-Bis-(*tert*-butoxycarbonyl)amino-4,6-dichloropyrimidine (5): Di-*tert*-butyl dicarbonate (9.62 g, 2.2 equiv) was added to a solution of 2-amino-4,6-dichloropyrimidine (3.24 g, 19.8 mmol) and 4-dimetylaminopyridine (244 mg, 0.1 equiv) in dry THF (30 mL). The reaction mixture was stirred at room temperature for 16 h. Then a small amount of water was added to the reaction mixture to quench the reaction. The solvent was removed under vacuum. The resulting residue was subjected to chromatography (Al_2O_3, *n*-hexane/ethyl acetate = 50:1–30:1). Compound **5** was obtained as a white solid. Yield: 6.97 g (97 %); m.p. 49.1–51.0 °C; ^{1}H NMR (400 MHz, $[D_6]$DMSO): $\delta = 1.43$ (s, 18H), 8.06 ppm (s, 1H); FAB MS: *m/z* calcd for $[M+H]^+$: 364.1; found: 364.1

2-Amino-4,6-bis[6-(dodecylamino)pyridine-2-yl]pyrimidine (1): Compound **4a** (1.40 g, 3.19 mmol), compound **5** (546 mg, 1.50 mmol), and tetrakis(triphenylphosphino)palladium (200 mg, 0.175 mmol, 5 mol %) in degassed DMF (10 mL) were heated at 110 °C for 15 h. The reaction mixture was concentrated under vacuum. The resulting solid was dissolved in chloroform and subjected to chromatography (Al_2O_3, *n*-hexane/ethyl acetate = 20:1). Recrystallization from MeOH gave Boc-protected compound **1** as a white solid. Yield: 1.80 g (67 %); ^{1}H NMR (400 MHz, $[D_1]CHCl_3$): $\delta = 8.92$ (s, 1H), 8.37 (d, $J = 8.2$ Hz, 2H), 8.20 (d, $J = 7.6$ Hz, 2H), 8.07 (s, 2H), 7.87 (t, $J = 7.8$ Hz, 2H), 2.46 (t, $J = 7.6$ Hz, 4H), 1.77 (m, 4H), 1.42 (s, 18H), 1,24 (m, 32H), 0.85 ppm (t, $J = 6,4$ Hz, 6H); FAB MS: *m/z* calcd for $[M+H]^+$: 844.6; found: 844.5.

Trifluoroacetic acid (1.14 g, 20 equiv) was added to a solution of the Boc-protected compound **1** (422 mg, 0.5 mmol) in dichloromethane (8 mL). The reaction mixture was stirred at room temperature for 6 h. It was then washed with a saturated aqueous solution of $NaHCO_3$ (10 mL) and water (10 mL). The solvent was evaporated under vacuum. The resulting solid was recrystalized from 1-propanol to give the desired compound **1** as a white solid. Yield: 270 mg (84 %); m.p. 179.7–180.5 °C; ^{1}H NMR (400 MHz, $[D_1]CHCl_3$): $\delta = 8.37$ (s, 1H), 8.33 (d, $J = 8.2$ Hz, 2H), 8.25 (br s, 2H), 8.07 (d, $J = 7.2$ Hz, 2H), 7.84 (t, $J = 8.2$ Hz, 2H), 5.21 (br s, 2H), 2.33 (t, $J = 7.6$ Hz, 4H) 1.70 (m, 4H), 1.25 (m, 32H), 0.85 ppm (t, $J = 6.4$ Hz, 6H); FAB HRMS: *m/z* calcd for $[M+H]^+$: 644.46520; found 644.46435; elemental analysis calcd (%) for $C_{38}H_{57}N_7O_2$: C 70.88, H 8.92, N 15.23; found: C 70.84, H 9.01, N 15.05.

2-Amino-4,6-bis[6-(ethyrylamino)pyridine-2-yl]pyrimidine (2): Compound **2** was synthesized by a similar procedure to that described for compound **1**. M.p. >268.0 °C (decomp.); ^{1}H NMR (400 MHz, $[D_1]CHCl_3$/$[D_6]$DMSO): $\delta = 9.50$ (s, 1H), 8.14 (s, 1H), 8.01 (d, $J = 7.8$ Hz, 2H), 7.78 (d, $J = 7.8$ Hz, 2H), 7.53 (t, $J = 7.8$ Hz, 2H), 5.42 (br s, 2H), 2.33 (m, 4H), 0.93 ppm (t, $J = 7.8$ Hz, 6H); FAB HRMS: *m/z* calcd for $[M+H]^+$: 392.18350; found: 392.18363.

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$$\frac{2[\mathrm{M}_2]}{c} = \frac{\delta_0 - \delta_i}{\delta_0 - \delta_d} \quad (3)$$

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