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Self-Assembling Structures of Long-Chain Phenyl Glucoside Influenced by the Introduction of Double Bonds

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Self-assembled nanostructures of amphiphiles held together by noncovalent interactions are currently the focus of interest due to their potential application in controlled release, electroactive composites, and multifunctional materials.[1−7] Literature study[1,7] reveals that tube-forming amphiphiles which mediated helical ribbon require unsaturation in the lipophilic moiety to impart a bent structure, leading to the induction of the supramolecular chirality, although the evidence is limited.

Fuhrhop and co-workers have mainly studied morphologies of amphiphiles affected by the introduction of different hydrophilic parts such as glucose-, galactose-type sugar, noncyclic-sugar moieties, and amino acids.[7a−b] However, there have never been any systematic studies on the influence of unsaturation, that is, the number and the position of the double bond units, or on the self-assembly of synthetic amphiphiles into high-aspect-ratio nanostructures (HARNs) based on solid chiral bilayers, even though the tubular structure of amphiphiles was already reported by several groups.[1,5,7] We herein report the self-assembly of a series of long-chain phenyl glucosides **1**−**4** varying in number of cis double bonds (0−3) in the lipophilic part. We studied their influence on the final morphologies by energy-filtering transmission electron microscopy (EF-TEM), SEM, CD, FT-IR, and XRD.

Compounds **1**−**4** were synthesized according to a similar method reported previously (Supporting Information).[2d] The gel-to-liquid crystalline phase transition temperature of the hydrated matrix lipids **2**−**4** is found to be 90.0, 65.2, and 50.1 °C, respectively, showing 40−70 °C higher values as compared with those of related glucopyranosides **6**−**8** lacking the amide group (Supporting Information).[6b] This situation enables us to compare self-assembled morphologies from **1**−**4** in a solid state. To date, no systematic self-assembly study using multiple components **5**−**8** with unsaturated bonds was achieved because the diene and triene derivatives **7** and **8** are existing as liquid crystals at room temperature.

The self-assembly of the matrix lipids **1**−**4** occurred rapidly under mild conditions. For example, 30 min of vortexing at 100 °C and 5 h of room-temperature incubation were sufficient to ensure the formation of stable supramolecular assemblies in aqueous solutions for **2**−**4**. However, **1** was insoluble in water and only formed a typical nanofiber structure with 100−350 nm diameters and several micrometers of length in a mixture of water and methanol (1:1 v/v). Figure 1 displays SEM and TEM images of the self-assembled **2**−**4** in aqueous solutions. Compound **2** shows the twisted fiber structure with 50−200 nm widths and several micrometers of length (Figure 1a), whereas **3** shows the left-handed coiled tube with 150−200 nm inner diameters and ca. 20 nm of wall (Figure 1b, less than 5%), and the helical ribbon (Figure 1c, Supporting Information) structures as the major morphology, showing the influence of double bonds on the final morphology of the self-assembled structures.

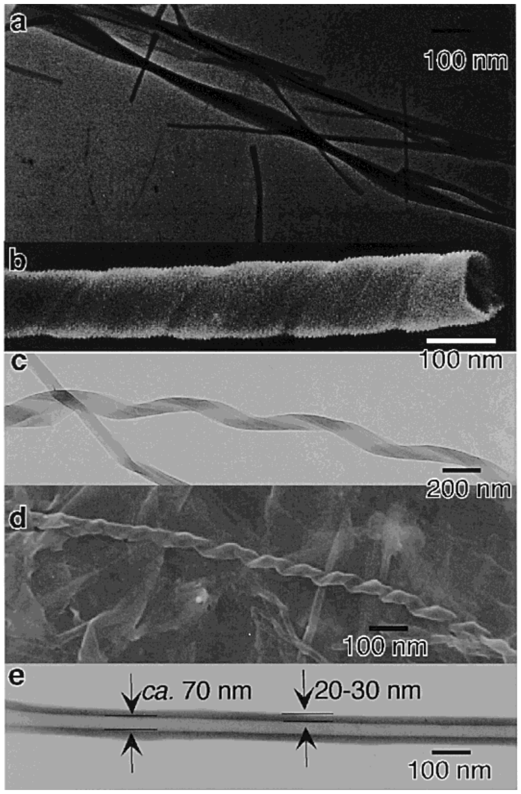

Figure 1. EF-TEM and SEM pictures of the self-assembled (a) **2**, (b and c) **3**, and (d, and e) **4**.

On the other hand, compound **4** possessing three cis double bonds in the lipophilic region displays the helical ribbon morphology with 80−100 nm of outer diameters and the nanotubular structure as the major morphology with ca. 70 nm of inner diameters and a wall thickness of 20−30 nm (Figure 1d and 1e, Supporting Information). As far as can be determined, all chiral structures possess a left-handed helical motif. These observations support the view again that the unsaturated units are important to produce nanotubes by self-assembly.

As alternative evidence for the nanotube formation of **3** and **4** in the microscopic structural view, we carefully observed CD

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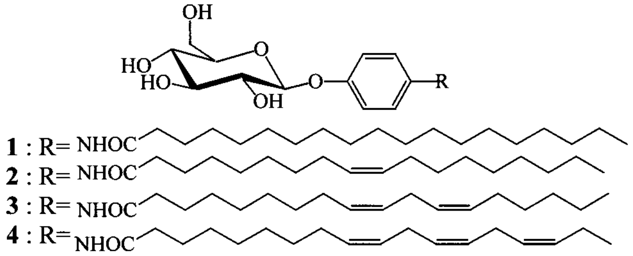

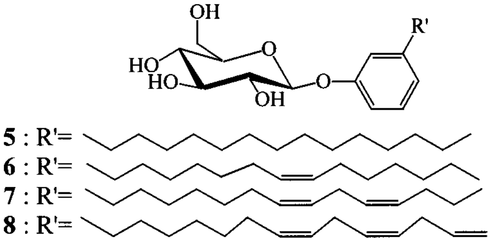

spectra of the self-assembled **2**−**4**, as shown in Figure 2. CD spectra of the self-assembled **3** and **4** in aqueous solutions show a strong negative band at 225 and 237 nm, respectively, forming nanotubular structures by chiral assembling, while they show only a weak CD signal at temperatures above a phase transition temperature (Figure 2 and Supporting Information) and shifted to longer wavelength, which is probably composed of monomers or small lipid aggregates, such as micelles or vesicles. The CD signal, however, became strong again when the lipid self-assembled to form a nanotubular structure after several hours. On the other hand, the CD spectrum of the self-assembled **2** in aqueous solution shows a much weaker negative band in comparison to **3** and **4**, suggesting that the self-assembled **2** forms a disordered chiral packing structure. The CD results provide direct evidence for chiral molecular architecture in nanotube and that the molecular packing of **3** and **4** is loosely chiral at temperatures above the phase transition temperature. Furthermore, phase transition temperatures of **3** and **4** are much higher than those of glucoside amphiphiles **6**−**8** lacking the amide group,[6b] indicating that the stabilization of self-assembled tubes **3** and **4** was enhanced by mainly an intermolecular hydrogen-bonding interaction between the amide groups. In addition, the contribution of linear dichroism (LD) for the self-assembled samples is negligible using the conventional LD mode.

What would be the difference in the molecular packing structure between the nanotubes from **3** and **4** and the twisted fiber from **2**? First, the molecular length of three amphiphiles was calculated by CPK modeling on the basis of single crystalline data of oleic acid, linoleic acid, and linolenic acid.[8] They showed almost similar values despite the bending effect. Second, X-ray diffraction patterns were measured. The small-angle diffraction patterns of the nanotubes **3** and **4** showed at least four ordered reflection peaks with a long period of 4.62 nm, which is smaller than twice the extended molecular length of **3** (3.15 nm by the CPK molecular modeling) and **4** (3.02 nm), but larger than the length of one molecule. These results strongly suggest that the self-assembled **3** and **4** form a bilayer structure with a relative small region interdigitated by a hydrophobic interaction (Support Information). On the other hand, the diffraction diagram of the microcrystalline solid **2** (one molecular length: 3.03 nm) formed a bilayer structure with 3.59 nm, supporting that **2** maintains a much stronger interdigitated bilayer structure between lipophilic regions than those of **3** and **4**. According to CD and powder X-ray diffraction results, the relatively strong intermolecular hydrogen-bonding interaction of an glucopyranoside moiety of **3** and **4** provided a highly ordered chiral packing structure even though they form a weak hydrophobic interaction between lipophilic groups, which lead to the formation of the nanotubular structure.

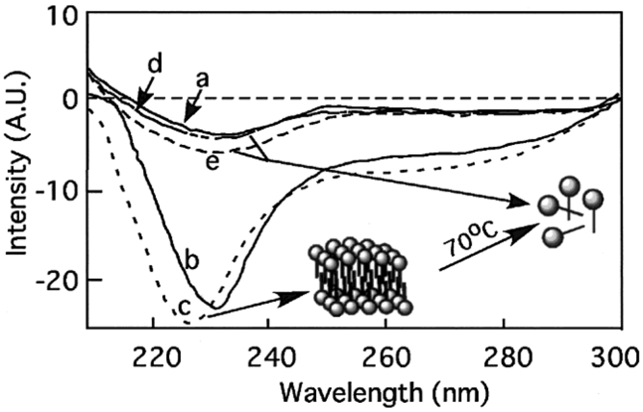

Figure 2. CD spectra of the self-assembled (a) **2**, (b) **3**, (c) **4** at 25.0 °C, (d) **3**, and (e) **4** at 70.0 °C, respectively.

In addition, **2** shows a highly ordered structure in the aliphatic region, possibly due to hydrocarbon crystallization, further supported by Fourier transform infrared (FT-IR) spectroscopy studies of the C−H stretching values at 2855 cm^{-1} of **3**−**4**, and 2851 cm^{-1} for **2**. It is reasonable to argue that the lipophilic group of **3** and **4** possessing three cis double bonds formed a much more disordered structure than that of **2**. Also, C═O (amide I) stretching patterns of the three compounds **2**, **3**, and **4** are different: **3** and **4** appeared at 1649 cm^{-1}, whereas **2** appeared at 1656 cm^{-1}, suggesting that **3** and **4** maintain a well-ordered structure of glucopyranoside headgroups by the intermolecular hydrogen-bonding interaction between amide groups.

In conclusion, the present study has demonstrated that long-chain phenyl glucoside formed twisted nanofiber, helical ribbon, and nanotubular structures depending on the unsaturation of the double bonds. These results are the first example for the systematic study on the influence of cis double bond units in the hydrophobic portion on self-assembled morphologies.

Supporting Information Available: Synthetic scheme for compounds **1**−**4**, phase transition temperature and IR results, SEM and TEM pictures of the self-assembled **2**−**4**, possible self-assembled molecular packing structures (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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