Formation of Lyotropic Liquid Crystals from a Fatty Acid and a Nitrogenous Heterocyclic Compound in Water

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Lyotropic liquid crystalline (LLC) phases of lauric acid in water have been successfully constructed with the aid of a N-heterocyclic compound in water. This novel ternary system can exhibit L_α phase with its lamellar spacing changing regularly in a wide concentration range.

Small molecules may self-assemble into an ever more complex hierarchy using a number of weaker supramolecular interactions, such as hydrogen bonds and π–π interactions, which govern the assembly of natural things like water and cells and make them knit together. As one of the most important self-assembled structures, LLC phases have been extensively studied and documented.[1,2] They are also important components of nature and the human body and exhibit a rich polymorphism of structures that have long-range periodicities with their characteristic repeat distances ranging from 2 to 15 nanometers.[3] Such characteristics make them more attractive in biology, nanotechnology, foods, pharmaceutics, and cosmetics.[4,5] Therefore, it is highly motivating to construct novel biocompatible LLCs.

Fatty acids exist in large amount and most of them are widely encountered in pure form in nature. Acting as central constituents of biological membranes, energy storage compounds, covalent modifiers governing the localization of proteins, etc.,[6] they fulfill a variety of vital functions. However, self-assembling properties to LLC from fatty acids have hardly been noticed and mentioned. Experiments show that pure fatty acids cannot produce LLC in water either at room or higher temperatures, although their alkali soaps like sodium laurate, myristate, palmitate, and stearate could form mesophases in water at high temperatures.[7] This may be due to their weak hydrophilic properties of the carboxyl group compared with sodium carboxylate. Their poor solubility in water is also a reason despite their similar structures to the amphiphiles. Thus, constructing the lyotropic phases of fatty acids without their alkali salts is an interesting challenge. Based on this motivation, we choose a highly hydrophilic nitrogenous heterocyclic compound here to improve the hydrophilic properties of fatty acids through noncovalent interactions. To our best knowledge, such a hydrogen-bonded complex from fatty acid to fabricate LLC phase at room temperature is a novel attempt.

Our system is composed of molecules of lauric acid, *N*-methylimidazole, and water. First, a hydrogen-bonded complex between the lauric acid and *N*-methylimidazole is prepared through adding *N*-methylimidazole to ethanol solution containing lauric acid and then ethanol is removed. Because the hydrogen bonds could be formed either between the nitrogen atoms of the imidazole ring and hydroxy or between the carbonyl and the

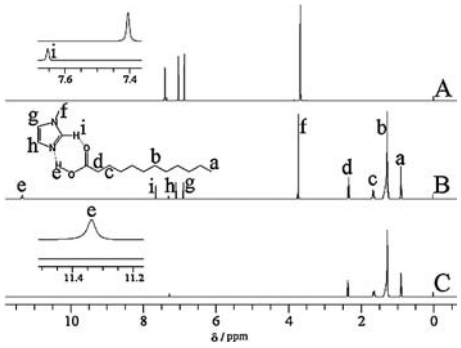

Figure 1. ^{1}H NMR spectra of *N*-methylimidazole (A), lauric acid (C), and their hydrogen-bonded complex (B).

H atom of –N–CH–N–,[8,9] the complex structure is thus deduced to consist of a seven-member ring with two hydrogen bonds,[10,11] in which each molecule acts both as a proton donor and also as an acceptor to ensure the stability of the complex (Figure 1B).[11] Such a structure is also supported by ^{1}H NMR data (Figure 1), where the H atom of –N–CH–N– is sheltered by an electron-withdrawing O atom and is, therefore, responsible for the chemical shift moving from 7.40 to 7.63 ppm. Another much unshielded proton peak of –N···H–O– by electron-withdrawing O and N atoms appears at 11.33 ppm. Meanwhile, nearly no change could be noted for other ^{1}H NMR signals when comparing with those of lauric acid and *N*-methylimidazole. Thus, a hydrogen-bonded amphiphile structure of lauric acid and *N*-methylimidazole can be concluded to form as that shown in Figure 1B.

Lyotropic liquid crystalline phases of this complex are then constructed using similar procedures as reported previously.[2,12] From representative visual appearances for samples of pure lauric acid and complex with different concentrations in water,[13] we can see that the pure lauric acid is insoluble in water. At a very low complex content less than 2% (weight percentage, thereinafter), crystalline precipitates are observed in the sample and are confirmed to be lauric acid by ^{1}H NMR, which could be attributed to the breakage of H bonds in complex by the large amount of water and, therefore, induced separation of lauric acid. With increasing complex concentration, the originally separated two phases become merged, milky-white with some weak birefringent regions being found. At higher complex content, the system gradually turns transparent, viscous, and more birefringent. But, high complex concentration over 88% changes the sample to a transparent isotropic solution. The regions showing LLC phase are confirmed further by polarized optical microscopy (POM) to extend from the complex concentration of 2% to 88%. Figure 2 shows the photographed textures of samples with

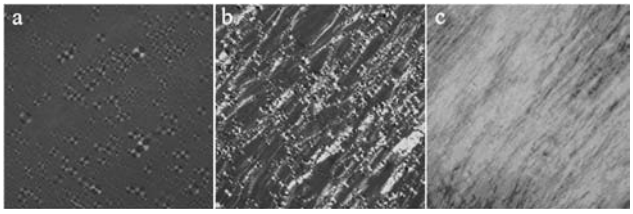

Figure 2. Polarized optical micrographs of the anisotropic LLC mesophase for representative samples. The complex concentration (wt %): 5 (a), 20 (b), and 60 (c).

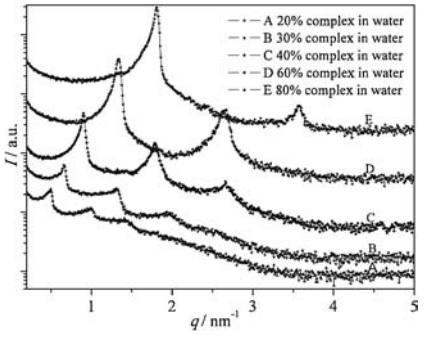

Figure 3. SAXS curves for the mesophases in the hydrogen-bonded amphiphile–water system with different complex concentrations.

different complex concentrations in water by POM. The typical "Maltese crosses" or "thread-like" textures can be assigned to a lamellar liquid crystalline phase (L_α).[14]

Further structural information on such lamellar liquid crystalline phases is extracted by small-angle X-ray scattering (SAXS) measurements. The scattering profiles for samples in the L_α region exhibit two or more Bragg peaks with their positions (scattering factor) obeying the 1:2:3 relationship (Figure 3) for a lamellar structure.[2,12] The lattice spacing values (d, calculated from the scattering factor corresponding to the first Bragg peak)[12] are 12.41, 9.34, 6.91, 4.67, and 3.45 nm for 20%, 30%, 40%, 60%, and 80% complex concentration, respectively, indicating a shrinkage of interlamellar distance with decreased water content. The linear change of lattice spacing (d) with water content[13] reflects a typical one-dimensional swelling scheme for the uptake of water by L_α phase. The hydrophobic component layer has a relatively constant thickness and stable molecular packing, while the water layer expands in a regular manner with its content.

How can the lauric acid form LLC phases so easily with the aid of *N*-methylimidazole in such a wide concentration range? Three driving forces can be considered to be mainly responsible for such an ordered assembly. One is the hydrophobic interaction between water and hydrophobic parts (long chain) of lauric acid, which is a very important driving force for individual hydrophobic molecules to assemble into larger ordered structures like LLC.[2,12] Such an attraction force may cause clustering of hydrophobic chains and induce self-assembling of water, *N*-methylimidazole, and carboxyl units of lauric acid in the hydrophilic region. The other main driving force should be attributed to H-bonding interaction, which can exist not only between the lauric acid and *N*-methylimidazole but also between *N*-methylimidazole or lauric acid and water. The constructed H-bond network among *N*-methylimidazole, carboxyl, and water in the hydrophilic portion may modify the polar head of lauric acid to make it have a suitable amphiphilic property to aggregate into LLC structure. In the investigated system here, the third role played by π–π interactions of *N*-methylimidazole is also important,[15] which can promote the lamellar packing of the LLC phases. Therefore, the combination of these interactions results in the formation of L_α phase in such a wide concentration range.

Subsequently, other fatty acids like capric, myristic, and palmitic acids are used to carry out similar self-assembly experiments. The obtained results also prove the formation of LLC phases with mainly L_α structure. Thus, we can conclude that the fatty acids, even carboxylic acids with long branched chains, can form LLC phases with the aid of an appropriate *N*-heterocyclic compound.

In conclusion, the lamellar lyotropic liquid crystalline phases of lauric acid in water have been successfully constructed with the aid of a N-heterocyclic compound in this work. This novel ternary system can exhibit L_α phase with its lamellar spacing changing regularly in a wide concentration range. Such work provides a simple method to construct LLC phases by hydrogen-bonded amphiphile and can be applied to design other supramolecular systems. Owing to the importance of fatty acid on vital functions, the LLC phases of fatty acids promise also a potential essentiality in biology, such as drug delivery and transport of fatty acids in the body.

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