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Templated Mineralization of Peptide-Based Unsymmetric Bolaamphiphiles

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Synthetic mimics of biology continuously evolve in sophistication and complexity to match structures commonly formed in nature. Peptide-based bolaamphiphiles represent a compelling case of biologically inspired molecules designed to achieve this goal. Similar to peptide-based biological molecules that adopt secondary structures such as α helices and β sheets, bola-form molecules utilize various attractive interactions to arrange into complex, self-assembled molecular formations.[1−7] Bolaamphiphiles, molecules with two hydrophilic headgroups joined by a hydrophobic, often oligomeric, linkage can self-assemble into structures that resemble those occurring in nature, such as lipid bilayers and amyloid fibers.[8,9] Previously, our laboratory reported the templating of inorganic compounds using liquid crystals, yielding solids with nanoscale features characteristic of the organic mesophase.[10−13] Recent reports of bolaamphiphiles templating metal and silica structures have also emerged.[5,14−16] In the work presented here, we report the template synthesis of cadmium sulfide (CdS) by a novel class of unsymmetric bolaamphiphiles containing peptide segments, which self-assemble into nanofibers. The resultant one-dimensional CdS nanostructures have widths of approximately 25 nm, with lengths of up to 1 μm.

As shown in Figure 1, the template molecules are bolaamphiphiles containing an oligomer of ethylene oxide at one terminus and a polypeptide segment of α-amino acids at the opposite terminus. The hydrophobic middle connecting each end contains a sequence of β-amino acids (β-alanine), *p*-aminobenzoic acid (PABA), and 6-aminohexanoic acid, which are capable of intermolecular hydrogen bonding and $\pi-\pi$ stacking. For bolaamphiphile **1**, the (L-glutamyl)$_3$glycine terminus was synthesized and characterized as previously

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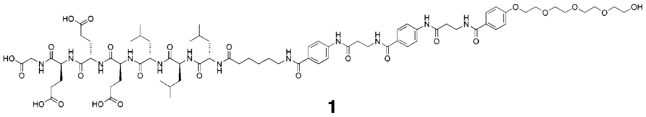

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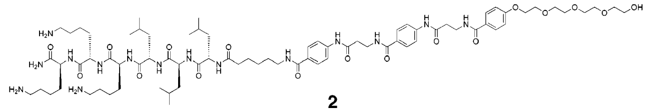

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Figure 1. (L-Glutamyl)$_3$glycine-terminated bolaamphiphile (**1**); (L-lysine)$_3$-terminated boloaamphiphile (**2**).

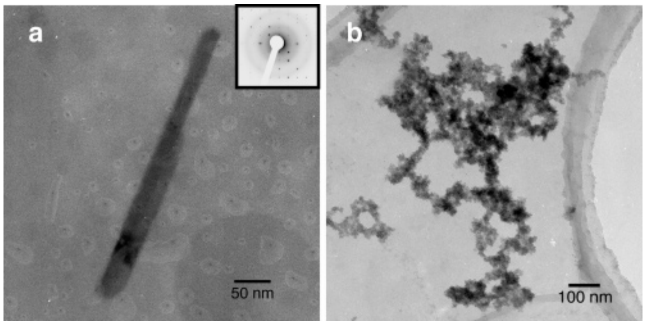

Figure 2. Cd(NO$_3$)$_2$ single crystal (a) and nontemplated CdS (b) from bolaamphiphile **1**.

reported;[17] the (L-lysine)$_3$ end group of bolaamphiphile **2** was synthesized in a similar manner, using a Rink amide resin. Bolaamphiphile **2** is soluble in neutral and acidic water and forms self-supporting gels as a result of nanofiber formation as solutions are exposed to ammonium hydroxide vapor.

We found that clear, colorless, and birefringent gels form from **2** with concentrations as low as 0.5 wt %. Circular dichroism (CD) spectroscopy of isotropic solutions at pH 6 suggests that peptide segments exist mostly in random coil conformations; however, at pH 11 nanofibers form and assemble, as indicated by a significant β-sheet signature in the CD spectrum (see Supporting Information). These results are consistent with those previously reported for molecule **1**[17] and demonstrate that solutions of **1** and **2** undergo similar changes in secondary structure upon gelation.

Self-assembled gels containing 1 wt % amphiphile were analyzed with a conventional transmission electron microscope (TEM). The bright-field image of a gel sample of **1**, negatively stained with a 2 wt % solution of phosphotungstic acid (PTA), shows one-dimensional objects that aggregate along their long axis. Individual components of these bundles are 5 nm in width, with lengths in excess of 1 μm. PTA-stained samples of a 1 wt % gel of **2** revealed similar nanofiber bundling as observed in **1**, with fiber widths of 6 nm and lengths up to 1 μm (see Supporting Information).

Cadmium sulfide mineralization of bolaamphiphiles **1** and **2** was carried out by suspending 10 mg of 1 wt % gels in a dilute aqueous solution of Cd(NO$_3$)$_2$ to obtain a 1:1 bolaamphiphile to Cd^{2+} ion ratio and solution pH of approximately 6. Samples were exposed to H$_2$S(g) for 12 h, and the precipitate was examined with a TEM. Interestingly, treatment of **1** resulted primarily in the formation of Cd(NO$_3$)$_2$ single crystals with little CdS present (Figure 2a). The single crystals were typically needlelike in appearance. This is surprising considering the solubility of the cadmium salt in water (1.7 g/mL)[18] and the highly favorable reaction of the salt with hydrogen sulfide (i.e., when bolaamphiphile **1** is absent from the cadmium nitrate solution, CdS readily forms). The CdS, when present, had neither the characteristic appearance nor nanoscale structure, indicating templating had occurred (Figure 2b). This nontemplated CdS had an appearance similar to that precipitated from Cd(NO$_3$)$_2$ and H$_2$S in water without a template. Additionally, this bulklike CdS was found to be of the thermodynamically stable wurtzite polymorph.

In sharp contrast to mineralization attempts with **1**, TEM characterization of cadmium sulfide formed in the presence of bolaamphiphile **2** shows very high aspect-ratio inorganic structures intimately associated with the organic template (Figure 3). These structures are comprised of CdS with the zinc blende crystal polymorph, as determined by electron diffraction, which is the kinetically favored product and characteristic of syntheses with liquid crystal and supramolecular templates.[10,12,19] In the present example, the inorganic structures resemble the amphiphilic nanofibers present in the aqueous gels and suspensions prior to mineralization. The CdS nanostructures had widths up to 25 nm and lengths on the order of 1 μm in length. These one-dimensional structures also display a low-contrast middle region that runs parallel to their long axis (Figure 3 inset; lower left). This low-contrast region is approximately 6 nm wide, which matches the outer diameter of the organic nanofibers. The increased width of the CdS structures, relative to the organic nanofibers, can be attributed to growth of the mineral phase after its initial nucleation and has been shown in other templating systems.[12]

To understand the different products obtained from mineralization experiments with **1** and **2**, the ^{1}H NMR spectra of dilute solutions of the bolaamphiphiles were analyzed. The spectra of samples, free of cadmium ions, were taken. It was expected that the carboxylic acid and amine groups would be involved in bolaamphiphile−ion interactions in **1** and **2**, respectively. After the addition of 1 molar equiv of cadmium ions, the spectrum of **1** reveals substantial peak attenuation within the peaks corresponding to ethylene oxide (δ 3.3−3.7). The chemical environment of the PABA aromatic moieties (located downfield; δ 7.0−7.8) is also affected, resulting in some attenuation as well. Conversely, no change in the ^{1}H NMR spectra of bolaamphiphile **2** solutions in the presence of the same concentration of Cd^{2+} ions is observed.[20]

The binding constants for Cd^{2+} in water (log k) to the model compounds oxydiacetic acid [O(CH$_2$CO$_2$H)]$_2$, methyl bis(3-aminopropyl)amine [CH$_3$(CH$_2$CH$_2$CH$_2$NH$_2$)$_2$], and 1,10-diaza-18-crown-6 were used to understand cadmium binding to the bolaamphiphiles. The binding constants have been reported as 3.0, 5.87, and 5.25, respectively.[21] From these values, in the case of bolaamphiphile **1**, Cd^{2+} would bind

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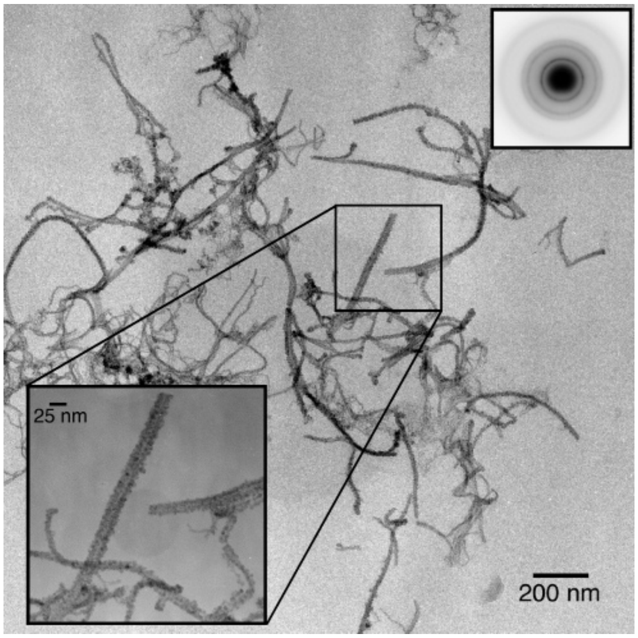

Figure 3. CdS templated from bolaamphiphile **2**; electron diffraction showing zinc blende crystal structure (upper right); templated nanowire (lower left).

preferentially to the ethylene oxide segments relative to carboxyl groups, prior to exposure to the H_2S gas. This is confirmed by the observed peak changes in the ^1H NMR spectra as well as with the absence of CdS templating by **1**. From the peak attenuated NMR spectra of samples of **1** containing Cd^{2+} ions, we conclude that the ions are primarily captured at the core of nanofibers and not bound to the carboxyl groups at the periphery. The reported binding constants indicate that the amine groups of bolaamphiphile **2** will have greater affinity for Cd^{2+} ions than the ethylene oxide segment, thus, promoting CdS mineralization at the nanofiber's exterior with exposure to H_2S gas, and do no lead to changes of the NMR spectra.

Template synthesis of CdS by an amine-terminated bolaamphiphile results in a one-dimensional hybrid structure. Transmission electron microscopy reveals CdS nanocrystals at the periphery, and the low-contrast region in the middle suggests that the core of the new hybrid structure is organic in nature. The observed differences between the two bolaamphiphiles, with regard to CdS morphology and yield, indicate organic molecule−ion interactions as a key factor controlling the nature of the templated mineralization.

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Supporting Information Available: CD spectra for **1** and **2** of the liquid and gelled states. Negatively stained TEM image of bolaamphiphile **2**. ^1H NMR spectra of the cadmium free and cadmium ion added solutions of **1** and **2**. This material is available free of charge via the Internet at http://pubs.acs.org.

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