# Self-assembled helical spherical-nanotubes from an L-glutamic acid based bolaamphiphilic low molecular mass organogelator†

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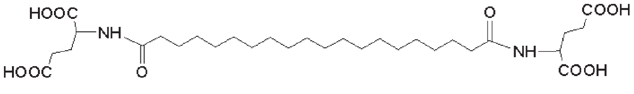
**An L-glutamic acid based bolaamphiphile was observed to self-assemble into a novel "helical spherical-nanotube" with a molecular monolayered structure within a tubular wall.**

Recently, there has been increasing interest in low molecular mass organogelators (LMOGs) that self-assemble into various nanostructures such as nanofibers, nanoribbons, and nanotubes.[1] Organogels could potentially be used in many fields such as template synthesis,[2] controlled release,[3] and functional materials.[4] Amino acid based amphiphiles have been paid much attention in the last few decades[5–8] since the amide and carboxylic acid groups can efficiently stabilize the self-assembled nanostructures through intra- and intermolecular H-bonds.[5] Amino acid based bolaamphiphiles are not only efficient gelators for various solvents, but they also form elegant nanostructures, in particular hollow nanotubes that are generally mediated from flat ribbons.[5,9–12] In this communication, we report a rare "helical spherical-nanotube" from an L-glutamic acid based bolaamphiphile, *N*,*N*-eicosanedioyl-di-L-glutamic acid (**EDGA**), which is also an efficient gelator for an alcohol–water mixture.



N,N-eicosanedioyl-di-*L*-glutamic acid (EDGA)

**EDGA** was synthesized by the amidation of L-glutamic acid diethyl ester with eicosanedioic acid and followed by the hydrolysis of tetraethyl *N*,*N*-eicosanedioyl-di-L-glutamic esters (**EDGEs**) to the free acid (see ESI, Scheme 1†). **EDGA** is soluble in methanol, ethanol, and 1-propanol, but insoluble in water, chloroform and other apolar solvents. Gelating tests revealed that no organogels were formed in pure alcohols. However, transparent organogels were formed with a 1 : 1 mixture of ethanol–water or methanol–water when a clear solution of **EDGA**, obtained by heating up to 70 °C for several minutes, was slowly cooled to room temperature (*ca.* 2–3 h). The minimum gelating concentration ($C_{\min}$)[1] under these conditions is *ca.* 0.22% (w/w) (3.3 mM $L^{-1}$) and 0.15% in a 1 : 1 mixture of ethanol–water and methanol–water, respectively. This indicated that **EDGA** is an effective gelator for 1 : 1 mixtures of both ethanol–water and methanol–water solvents.

AFM and TEM were used to characterize the nanostrutures of the organogels formed in the mixed solvents. In order to measure the AFM, freshly cleaved mica tied with a thread was put into the **EDGA** solution in a sealed tube and allowed to form organogels. The AFM image reveals that **EDGA** self-assembled into well-defined 1D nanostructures with lengths of up to tens of micrometers and diameters of ~40.0 nm (Fig. 1a). The enlarged AFM phase image reveals that the 1D nanostructures are left-handed helical nanotubes, mediated from curved helical ribbons (Fig. 1b). Sectional analysis (inset of Fig. 1b) confirms that the outer surface of the nanotube is curving towards the outside segment by segment. TEM observations taken from unstained xerogels further confirm that **EDGA** forms well-defined 1D nanostructures with the same curved feature of the tubular wall (Fig. 1c). The dark edges clearly reveal the tubular wall and the relatively bright center indicates the vacant inner part of the tube. The TEM image also reveals that the inner and outer surfaces of the tubular wall are all curved towards the outside segment by segment and cause the nanotube to be like a spherical condenser, which is usually used in chemical synthesis. Thus, the novel nanotubes may be named as "helical spherical-nanotubes". The helical spherical-nanotubes are obviously different from common nanotubes reported in the literature,[5,9–12] which are generally flat at the inner and outer surfaces of the tubes and the helical pitches are usually difficult to distinguish. In comparison with those reported nanotubes, it can be suggested that, in our case, the spherical-nanotube was converted from a bent ribbon, while the

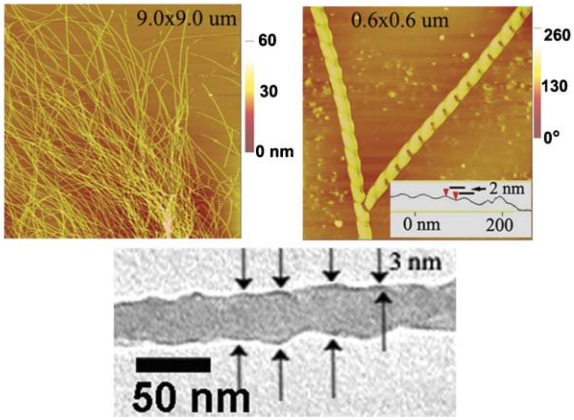


**Fig. 1** A large-scale height (a) and an enlarged phase (b) AFM image of helical spherical-nanotubes; inset of (b) is a section analysis of one nanotube in (b); (c) is a HRTEM image. All are obtained from a 1 : 1 mixture of ethanol–water at room temperature with $C_{\text{gel}}$ = 8.8 mM $L^{-1}$.

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† Electronic supplementary information (ESI) available: synthesis and experimental, AFM images, FT-IR and XRD spectra of the xerogels of **EDGA**, AFM images of the xerogels of both **EDGEs** and monocarboxylic sodium of **EDGA**. See http://www.rsc.org/suppdata/cc/b4/b413259a/

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conventional nanotubes were mediated from a flat sheet or ribbon.[1,11]

On the other hand, the 3.0 nm thick tubular wall estimated from the HRTEM image is very near to the molecular length ( ~3.1 nm) of **EDGA** based on the CPK (Corey–Pauling–Koltun) model. This suggests that the curved ribbons are in a molecular monolayered or bilayered structure within the tubular wall. The bilayer could be formed by the U-shaped **EDGA** molecules with the two hydrophilic head groups toward both surfaces of the tubular wall although this is rarely found in the self-assembly of amphiphiles.[5] In order to give a deeper insight into the driving force for the assembled nanostructure of **EDGA**, an FT-IR spectrum of the xerogels from **EDGA** with a 1 : 1 mixture of ethanol–water was measured (see ESI, Fig. 2). The strong vibration bands at 2849 and 2917 $cm^{-1}$ are assigned to the $CH_2$ symmetrical and antisymmetrical stretching vibrations, respectively. These two bands, without any shoulders at high wavenumbers, suggest the all-*trans* conformation of the alkyl chain in the gel.[5,13] This further verified that **EDGA** in the gel has formed into a stable monolayer lipid membrane (MLM), which is usually observed for bolaamphiphiles.[5,6,9–12] Such an MLM structure is further confirmed by the XRD pattern of xerogels (see ESI, Fig. 3), in which an obvious diffraction peak was observed at $2\theta = 3.0°$. The calculated *d*-spacing is ~2.9 nm, which is in an agreement with the molecular length. The driving forces for the formation of the MLM of **EDGA** are regarded to be due to both the H-bonds among the carboxylic acid/amide units and the hydrophobic interactions between the alkyl spacer. The amide-I and -II bands, which appear at 1641 and 1541 $cm^{-1}$ respectively, indicate the formation of the amide to amide H-bonds.[14] This can be supported further by the –NH stretching vibration band appearing at 3327 $cm^{-1}$. The vibration at 1729 $cm^{-1}$ is assigned to the C=O stretching vibration of H-bonded carboxylic acid groups, indicating the formation of intermolecular H-bonds between carboxylic acid units.[15] In addition, two vibrational bands are observed at 1594 and 1409 $cm^{-1}$, which are assignable to the antisymmetrical and symmetrical –C=O stretching vibration of the $–COO^-$ groups, respectively.[9] This fact indicates that part of the carboxylic acid has been hydrolyzed in a 1 : 1 mixture of ethanol–water solution and could be incorporated into the assembly of **EDGA**.

It should be noted that the free carboxylic acid groups play an important role in forming the helical structure. When **EDGEs** were used, only layered structures were seen (see ESI, Fig. 4). In addition, if **EDGA** was converted into a monosodium salt by adding an equal mole of NaOH into the solution of **EDGA** in a 1 : 1 mixture of ethanol–water with $C_{gel} = 8.8$ mM $L^{-1}$, only a very viscous liquid is formed after cooling. AFM observations revealed that the monosodium salt of **EDGA** also formed lamellar structures (see ESI, Fig. 5). The different self-assembled superstructures from the derivatives of **EDGA** clearly reveal that all four free carboxylic acid groups in the **EDGA** play an important role in the formation of the helical spherical-nanotubes.

In order to give a deep insight into the self-assembly of **EDGA** into the helical spherical-nanotubes, in particular the formation of curved ribbons, we used PCMODEL to examine the possible mechanism of self-assembly. The AFM observations of the supramolecular structures formed from **EDGA** and its diethyl ester and monosodium salt derivatives indicated that the four free carboxylic acid units are the key structure parameters for the formation of helical spherical-nanotubes. PCMODEL minimization (Fig. 2) indicates that **EDGA** tends to form dimer-like aggregates through the intermolecular H-bonds between carboxylic acid units and produces a twisted molecular assembly. The twist would therefore yield the curved edges of the molecular assembly, as shown in Fig. 2b. The amide groups being free of H-bonds would allow the further aggregation of the twisted molecular assembly driven by the formation of the amide to amide H-bonds between the adjacent molecular assemblies (Fig. 2b) and then form a curved helical ribbon (Fig. 2c), and a subsequent helical spherical-nanotube (Fig. 2d).

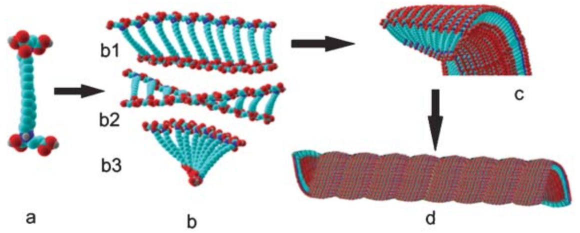

**Fig. 2** CPK model of **EDGA** (a), twisted molecular assembly of ten molecules through dimer-like intermolecular H-bonds between carboxylic acid groups (b), aggregates of twisted molecular assembly *via* amide to amide intermolecular H-bonds (c), and formation of helical spherical-nanotubes (d).

In conclusion, a newly synthesized bolaamphiphilic LMOG containing L-glutamic acid groups was found to gel a 1 : 1 mixture of alcohol–water with $C_{min} < 0.3\%$. It self-assembles into a novel helical spherical-nanotube with a molecular monolayered structure within the tubular wall.

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