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COMMUNICATION

Fabrication of well-defined crystalline azacalixarene nanosheets assisted by Se \cdots N non-covalent interactions†

Yu Yi,^a Shixin Fa,^b Wei Cao,^a Lingwu Zeng,^a Meixiang Wang,^c Huaping Xu^{*a} and Xi Zhang^a

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We have employed a selenium containing amphiphile to assist the formation of well-defined azacalixarene nanosheets, in which the Se \cdots N non-covalent interaction plays an important role.

Azacalixarene, a new kind of macrocycle with well-defined conformations and multiple nitrogen atoms, has recently drawn considerable attention in supramolecular recognition, gas storage, catalysis and enzyme mimics.^{1–6} One of the strategies to realize and enrich those functions is to prepare well-defined nano-crystals and to use their ordered structures and microenvironments.⁷ Until now, most of the well-defined crystals of heteracalixaromatics have been obtained in organic solvents. How to fabricate well-defined crystals of heteroacalixaromatics with controlled manner in aqueous solution remains a challenge.

Selenium is an essential trace element and micronutrient for the human body. Recent advances indicate that selenium has the potential application in various fields, including quantum dots,⁸ semiconducting conjugated materials for transistor and solar cell applications,^{9–15} responsive polymeric biomaterials for controlled drug delivery^{16–20} etc. Great effort has also been seen with mimics of glutathione peroxidase (GPx),^{21–25} a mammalian antioxidant seleno-enzyme that protects biomembranes and other cellular components from oxidative damage. It is found that intra-molecular Se···N non-covalent interactions are important in GPx and its mimics.^{26–30} However, inter-molecular Se···N non-covalent interactions have rarely been used as driving force for controlled self-assembly.

In this communication, we reported the fabrication of welldefined azacalix[6]pyridine (APy6) nanosheets in an aqueous solution (Scheme 1), which was assisted by inter-molecular Se \cdots N non-covalent interactions. In order to enhance the weak Se \cdots N non-covalent interaction for self-assembly, we employ a Se containing amphiphile (SeG), which has three hydrophilic branches with a Se atom in each branch, and an azacalixarene APy6 with twelve nitrogen atoms which can form both multiple Se \cdots N non-covalent interactions as well as hydrophobic interactions with the SeG molecules.

In a typical procedure, 2×10^{-6} mol SeG and 5×10^{-7} mol APy6 were mixed in dichloromethane, a good solvent for both molecules. The solvent was then removed under reduced pressure and 1 mL water was added. A turbid suspension was obtained after sonication for 2 min and the resulting solution was stood for 12 h before characterization.

To investigate the morphology of the nanosheets, transmission electron microscopy (TEM) and atomic force microscope (AFM) were employed. As shown in Fig. 1a and b, well-defined nanosheets which are 1–2 μ m long and 300–500 nm wide can be observed. Cryo-TEM images (Fig. S1, ESI†) also support the result and indicate that the formation of the nanosheets is in solution instead of on the substrates during the drying process. With the same preparation procedure, the amphiphilic SeG molecules form micelles in water with a diameter of 140 nm (Fig. 1c and S2a, ESI†) when they are above the critical micelle concentration (1.2 mM, Fig. S2b, ESI†). The insoluble APy6 molecules in aqueous solution only exist as irregular aggregates from TEM observations (Fig. 1d). Therefore, it can be speculated that the well-defined nanosheets are formed by both SeG and APy6.

In order to know whether the well-defined nanosheets are crystalline or not, TEM electron diffraction and X-ray diffraction (XRD) measurements were carried out. The electron diffraction pattern of the nanosheets suggest that they are a



Scheme 1 Fabrication of well-defined azacalix[6]pyridine nanosheets assisted by $Se \cdots N$ non-covalent interactions.

 ^a Key Lab of Organic Optoelectronics and Molecular Engineering, Department of Chemistry, Tsinghua University, Beijing, 100084, P. R. China. E-mail: xuhuaping@mail.tsinghua.edu.cn; Tel: +86-10-62773672

^b CAS Key Laboratory of Molecular Recognition and Function, Institute of Chemistry, Chinese Academy of Sciences, Beijing, 100190, P. R. China.

^c Key Laboratory of Bioorganic Phosphorus Chemistry & Chemical Biology, Department of Chemistry, Tsinghua University, Beijing, 100084, P. R. China.

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Fig. 1 TEM (a) and AFM (b) images of the nanosheets. Well-defined nanosheets which are $1-2 \mu m$ long and 300–500 nm wide are observed. TEM images of (c) the micelles of SeG in water with an average diameter of 140 nm, and (d) the irregular aggregates of the insoluble APy6 molecules in aqueous solution.

triclinic single crystal structure (Fig. 2a). XRD result shows the layer distance of the nanosheets are 0.93 nm (Fig. 2b), which agrees well with the vertical distance of the cell length corresponding to the face packing direction of APy6 molecules in single crystals (calculated as 9.35 Å, see ESI†).⁵ AFM was employed to measure the thickness of the nanosheets. The AFM height results show the thickness of the nanosheets varies from 24 nm to 35 nm (Fig. S3, ESI†), indicating that the nanosheets are composed of multi-layers. The results above indicate that the nanosheets are mainly constructed by the APy6 molecules as nano-crystalline structures.

We wondered whether SeG still existed in the nanosheets and whether the Se...N non-covalent interactions played an important role in the formation of the nanosheets, TEM-based energy dispersive spectroscopy (TEM-EDS), X-ray photoelectron spectroscopy (XPS), Fourier transform infrared (FT-IR) spectroscopy and ESI-Q-TOF spectrum were employed. TEM-EDS shows Se atoms are contained in the nanosheets even after being rinsed 5 times (Fig. S4, ESI[†]). Since the nature



To further study the Se. N non-covalent interactions between the SeG and APv6 molecules, three control experiments were carried out. Firstly, a non-selenium containing amphiphile, 1,3,5-tri(2,5,8,11-tetraoxadodecyl)benzene (OG) in which selenium atoms are replaced by oxygen atoms, is synthesized. Irregular aggregates are observed (Fig. 4a) with the same preparation procedure, indicating the important role of Se atoms played in the formation of the nanosheets. In addition, HCl (aq) and H₂O₂ (aq) were added to the suspension of the nanosheets so the final pH was 2 and the percentage of H_2O_2 was 1%. When treated by pH = 2 HCl (aq) for 12 h, the nanosheets are decomposed (Fig. 4b) because of the protonation of nitrogen atoms in the APy6 molecules. When treated by 1% H₂O₂ (aq) for 12 h, the surfaces of the nanosheets are partly destroyed (Fig. 4c) because of the oxidation of the Se atoms.^{17,19,20} Both the protonation of APy6 and the oxidation of SeG can disrupt the Se. . N noncovalent interactions as well as hydrophobic interaction and lead to the deformation of the nanosheets. These experiments indicate that the SeG and APv6 molecules are mainly combined in the outer layers of the nanosheets and the central part of them are mainly composed of APy6 molecules.

A possible mechanism is proposed to explain the formation of the nanosheets. It has been reported that the surfactants such as sodium dodecyl sulfate could affect the crystallization



Fig. 2 TEM electron diffraction pattern (a) and XRD (b) of the nanosheets. (a) The electron diffraction pattern of the nanosheets suggest that they are a triclinic single crystal structure. (b) The 001 and 002 peaks are 9.48° and 19.0° respectively, indicating that the distance between layers of the nanosheets is 0.93 nm.



Fig. 3 XPS analysis (a) and FT-IR spectrum (b) of the nanosheets on Si substrates. After the formation of the nanosheets, (a) the Se $3d^3$ biding energy of SeG shifts from 51.80 eV to 50.82 eV, while (b) the C–Se bond vibration shifts from 561 cm⁻¹ to 568 cm⁻¹, indicating the existence of the Se···N non-covalent interactions.



Fig. 4 Control experiments of (a) a non-selenium containing molecule OG with APy6, (b) nanosheets + HCl (aq) and (c) nanosheets + H_2O_2 (aq). Irregular aggregates are obtained with the OG molecule (a), indicating the important role played by Se atoms. Decomposing (b) and partly destroying (c) of the nanosheets are observed when treated by pH = 2 HCl (aq) and 1% H_2O_2 (aq) respectively.

and change the morphology of the crystals.^{33–35} In our system, the SeG molecules first serve as surfactants helping to dissolve the APy6 molecules and facilitate the crystal growth. Then parts of SeG and APy6 molecules are complexed together and adsorbed onto the surface of the nano-crystal to prevent growth of the face packing dimension to assist the formation of two dimensional nanosheets. In addition, the adsorption of the SeG molecules onto the nanosheets also prevents further growth of the crystals and finally well-defined nanosheets are obtained.

In conclusion, we have successfully fabricated well-defined azacalixarene nanosheets in aqueous solution. The experimental results indicate that the formation of the nanosheets is assisted by Se···N non-covalent interactions. It is greatly anticipated that Se···N or Se···X (X = Cl, Br, I) intra/inter molecular interactions will act as new driving forces for controlled self-assembly, leading to new GPx mimics or other functional supramolecular materials.

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