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One-pot Aqueous Phase Synthesis of Peptide-CdTe Quantum Dots

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Here, a facile strategy has been developed for the synthesis of peptide-capped CdTe quantum dots (peptide-QDs) in aqueous phase by one-pot method. The capping ligand, designed peptide can form a self-assembly hydrophobic layer on the surface of QDs, which make the peptide-QDs exhibit excellent stability in acidic and high salt solutions. The as-prepared peptide-QDs are of potential values in the applications of biosensing and bioimaging.

Peptides have recently attracted great attention in biochemistry and biomedicine because of the development of synthesis technology.[1-5] They play key roles in the drug industry, particularly in the study of skin care and other anti-aging products. Quantum dots (QDs) have unique fluorescent properties that are desirable for applications in biological imaging and in vitro diagnostics.[6-8] As a kind of biofunctionalized QDs, peptide-capped QDs have been applied in biosensing and bioimaging, such as detection of copper and silver,[9] fluorescence imaging of HIV-1 protease activity and G-protein coupling receptors in living cells.[10, 11] Several coating strategies have been developed. Firstly, ligand exchange approach is done by the thiol-containing peptide[12] but at the expense of compromised colloidal stability and reduced quantum yield; secondly, the negtively-charged QDs are conjugated to the positively-charged peptide by electrostatic interactions,[13] which could be affected by other charged substance; thirdly, the peptide-capped QDs can also be obtained by the bridge of biotin-avidin, with the challenges of the cost and the large hydrated diameter.[14] Recently, direct synthesis of peptide-capped QDs has been developed.[15, 16] However, most of the peptides-capped QDs are unstable under physiological conditions.

Based on these considerations, we report the design and synthesis of a short peptide-capped CdTe quantum dots (peptide-QDs) with extreme stability by one-pot method in this work. The hexapeptide (CCALNN) can be tethered to QDs by strong binding with Cd^{2+} ions, and form a passivated layer with hydrophilic terminus, which result in excellent stability of peptide-QDs in acidic and high salt solutions.. By optimizing the reaction conditions, the emission wavelengths of the peptide-QDs could be tuned from 525 to 600 nm with narrow full widths at half-maximum of 55~67 nm.

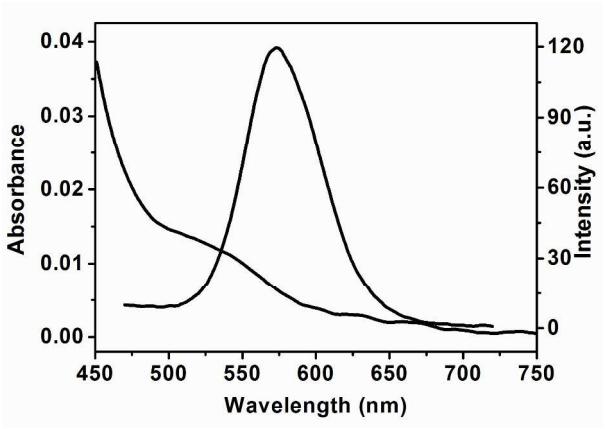

Fig. 1 UV-Vis absorption and Fluorescence spectra of peptide-QDs. (λ_{ex} = 350 nm)

Actually, similar peptide (CALNN) has been used as the stabilizer of gold nanoparticles.[17] Our group has used it to prepare the peptide-capped QDs by ligand exchange as well.[18] Cysteine (C) with the thiol group makes strong binding with Cd ions. Most importantly, alanine (A) and leucine (L) have the capability of self-assemble to form a hydrophobic layer, which can effectively prevent the oxidation of QDs.

Fig. 1 displays UV-Vis absorption spectrum and fluorescence spectrum of the peptide-QDs. The first excition absorption peak is obvious and the corresponding fluorescence emission is around 575 nm, which suggests that the peptide-QDs have the similar optical properties to the aqueous phase-synthesized QDs using other common ligands. The formation of peptide-QDs was visually confirmed by TEM. The peptide-QDs exhibit well monodispersity (Fig. 2A) and high crystalline structure observed from the high resolution TEM (HRTEM) image (Fig. 2B). The structure of the obtained QDs belongs to zinc-blende CdTe structure as demonstrated by the XRD pattern in Fig. 2C. Besides, the size distribution histogram was obtained by measuring more than 300 particles, and the average diameter of the peptide-QDs is 2.8 ± 0.85

nm (Fig. 2D). The above results demonstrate that the peptides can be used as the stabilizers to synthesize the CdTe QDs successfully in aqueous solution via a facile synthetic route.

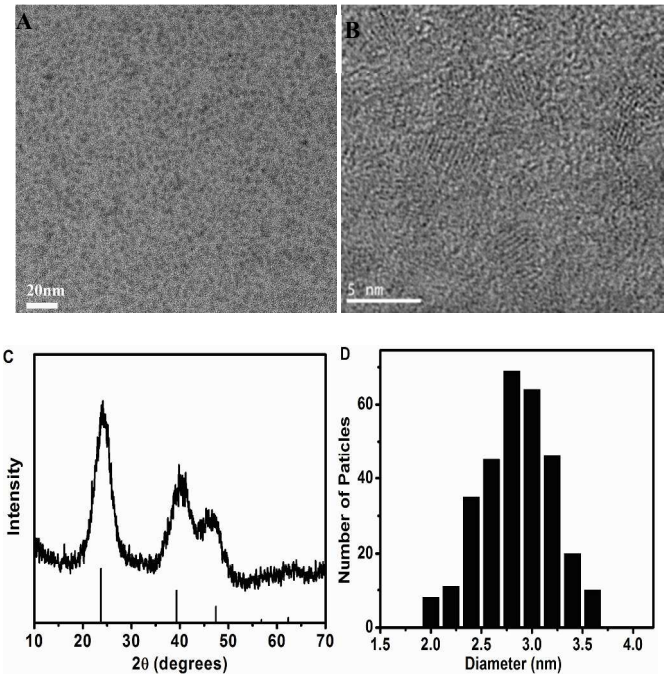

Fig. 2 (A) TEM, (B) HRTEM images, and (C) XRD pattern of the as-prepared QDs; the bottom lane in (C) is the standard pattern of CdTe QDs (JCPDs card 15-0770); (D) the size distribution from HRTEM images.

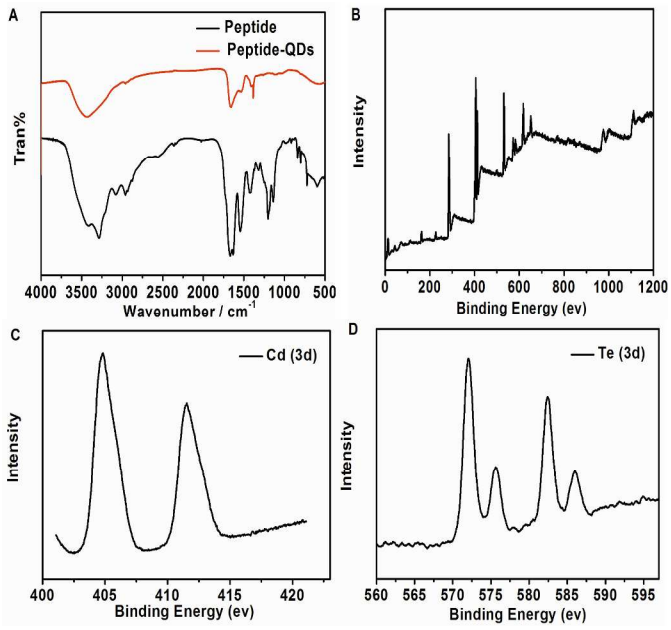

Fig. 3 (A) FTIR spectra of (black) free peptide and (red) peptide-QDs. (B) XPS spectra of peptide-QDs, and high revolution spectra showing (C) Cd (3d) and (D) Te (3d) energy, respectively.

To verify the existence of peptide on the surface of the prepared QDs as stabilizer, we compared the FTIR spectra of free peptide and peptide-QDs. As seen in Fig. 3A, the IR absorption bands of free peptide at 1640 and 1405 cm^{-1} are ascribed to $–COO^-$ groups, whereas the peak at 2558 cm^{-1} are assigned to –SH groups. By contrast, the disappearance of the -SH stretching vibrational peak in the IR spectrum of peptide-QDs clearly indicates that the thiol group of peptide binds onto the surface of the QDs through the Cd–S bond. As we know, the XPS measurements can provide information on the composition of QDs. Fig. 3B is the overall XPS survey spectra of the peptide-QDs, in which the typical characteristic peaks of Cd (3d) and Te (3d) of the QDs are distinguishable (Fig. 3C and Fig. 3D).

The pH of the precursors has a serious effect on the optical properties of QDs. In our experiments, different pH for the reaction from 8.0 to 11.0 were investigated under the same synthetic conditions (Fig. 4A). The fluorescence of the QDs was increased firstly from pH 8.0 to 10.0, and then decreased at 11.0. The optimal pH was found to be around 10.0. Considering that the peptides might hydrolyze under strong alkaline conditions, we selected 9.0 as the final pH to prepare QDs. The growing temperature is also an important parameter that greatly affect the quality of QDs. As shown in Fig. 4B, when the growing temperature increases from 70 ºC to 80 ºC, no fluorescence can be observed. The most likely reason for this is that the low temperature is not good for the formation of crystal nucleus for the growth of peptide-QDs. As the temperature continues increasing from 90 ºC to 100 ºC, the fluorescence intensity greatly increases and reaches the highest at 100 ºC which was chosen as the optimal temperature. It is also the optimal temperature for synthesis of many other ligands-capped QDs.[19-21] This temperature is suitable for the nucleus and growth of nanocrystals. Furthermore, the molar ratio between peptide and $CdCl_2$ that influences the fluorescence properties of peptide-QDs has been discussed (Fig. 4C). The ratio of 1:0.25 and 1:0.5 produced the fluorescent peptide-QDs successfully, and the optimal ratio was 1:0.5.

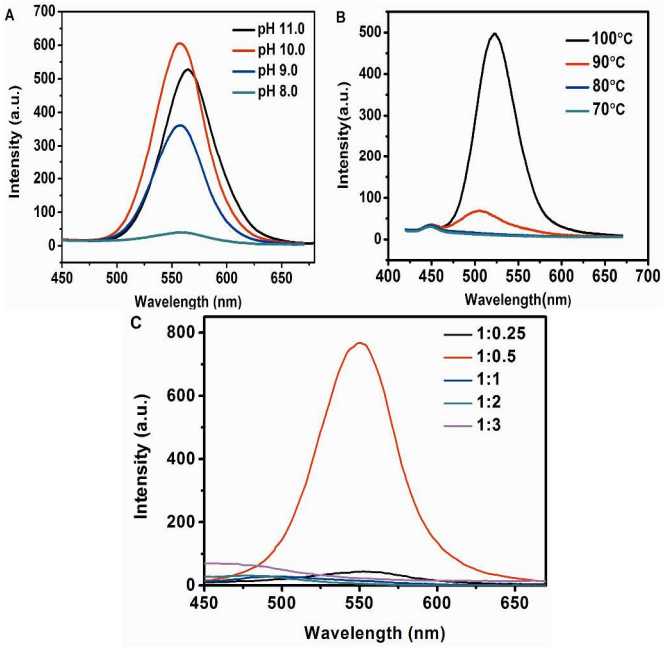

Fig. 4 Fluorescence spectra of peptide-QDs obtained at different (A) pH, (B) growing temperatures and (C) the ratios of $CdCl_2$: peptide.

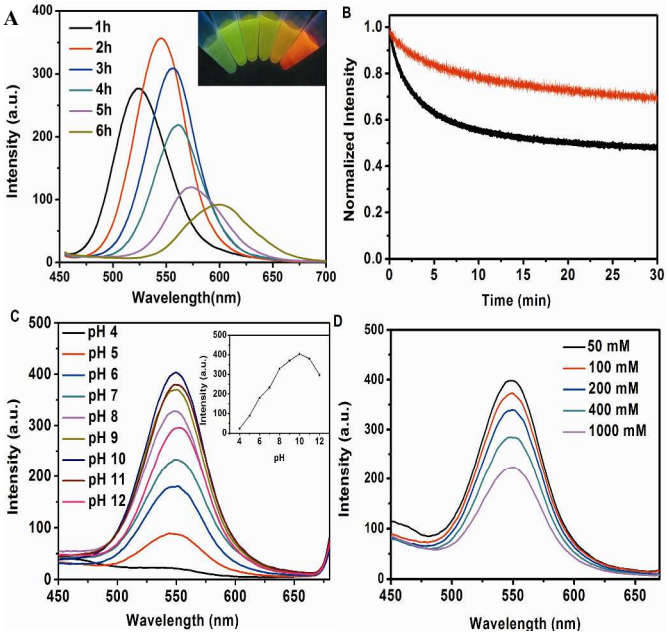

Fig. 5 (A) Fluorescence spectra of peptide-QDs prepared with different reaction times (1h, 2h, 3h, 4h, 5h, and 6h), Inset: the photos of as-prepared QDs under UV irradiation by digital camera; (B) the photostability of the peptide-QDs and GSH-QDs(80 nM, Xe lamp, 150 W, Ex: 350 nm,); (C) fluorescence spectra of peptide-QDs at different pH (40 nM, inset: the change of fluorescence intensity) and (D) different concentrations of NaCl at pH 7.4 (40 nM, 20 mM Tris-HCl buffer).

By simply changing the reaction time under the optimal conditions, we can get peptide-QDs with different emission wavelengths from 525 to 600 nm with narrow full widths at half-maximum of 55~67 nm (Fig. 5A), which display different colors from green to orange under UV light as shown in the photo of the original QDs solution (inset in Fig. 5A). The fluorescence intensity of peptide-QDs obtained by reacting for 2 h is the highest. Besides, the stability of fluorescent probes is critically important for biological applications.[22, 23] Fig. 5B displayes the photostability of the peptide-QDs and GSH-capped QDs, respectively. The fluorescence intensity of peptide-QDs is about 75% of the initial value after irradiation for 30 min. GSH consists of glutamate, cysteine, and glycine, which cannot form the hydrophobic layer. Thus, the phtotostability of GSH-capped QDs is relatively poor compared with peptide-QDs. We expected that the peptide-QDs with a hydrophobic shielding layer should be as extremely stable over a wide range of pH and salt concentration as the gold nanoparticles and QDs capped by the similar peptide.[17, 18]Actually, the peptide-QDs have good fluorescence over pH 5.0–12.0 (Fig. 5C). pH 4.0 which is lower than the pKa of asparagine (pKa = 5.4) results in the loss of charge of asparagine residue and the reduction of repulsion force between particles. Thus, the peptide-QDs became unstable and lost its fluorescence. Besides, the peptide-QDs exhibit the tolerance of high salt concentration as well (Fig. 5D). They maintain their stability and fluorescence when the concentration of NaCl is up to 1 M at pH 7.4. All of the above results indicate that the peptides-QDs have good optical property and stability.

Conclusions

In summary, the peptide-capped CdTe QDs were directly prepared by using peptides as the stabilizer in aqueous phase through a facile one-pot method. This synthetic process is simple and easy. Besides, the QDs display good photostability. Furthermore, special peptide-capped QDs can be prepared with the particularly designed useful peptides, which have great potential values in applications of biosensing and bioimaging.

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Notes and references

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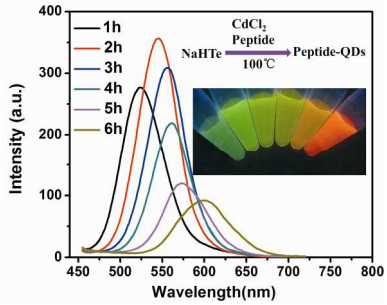

We report the design and synthesis of a short peptide (hexapeptide)-capped CdTe quantum dots (peptide-QDs) by one-pot method with excellent stability in acidic and high salt solutions.